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A Study of Vertical Air Motion and Particle Size in Showers Using a Doppler Radar

by P. G. F. CATON, M.A., Ph.D.

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Contents

Summary 1

Introduction 1

Method of analysis 2

Discussion of the minimum-velocity assumptions 3

Factors affecting the velocity spectrum width 4

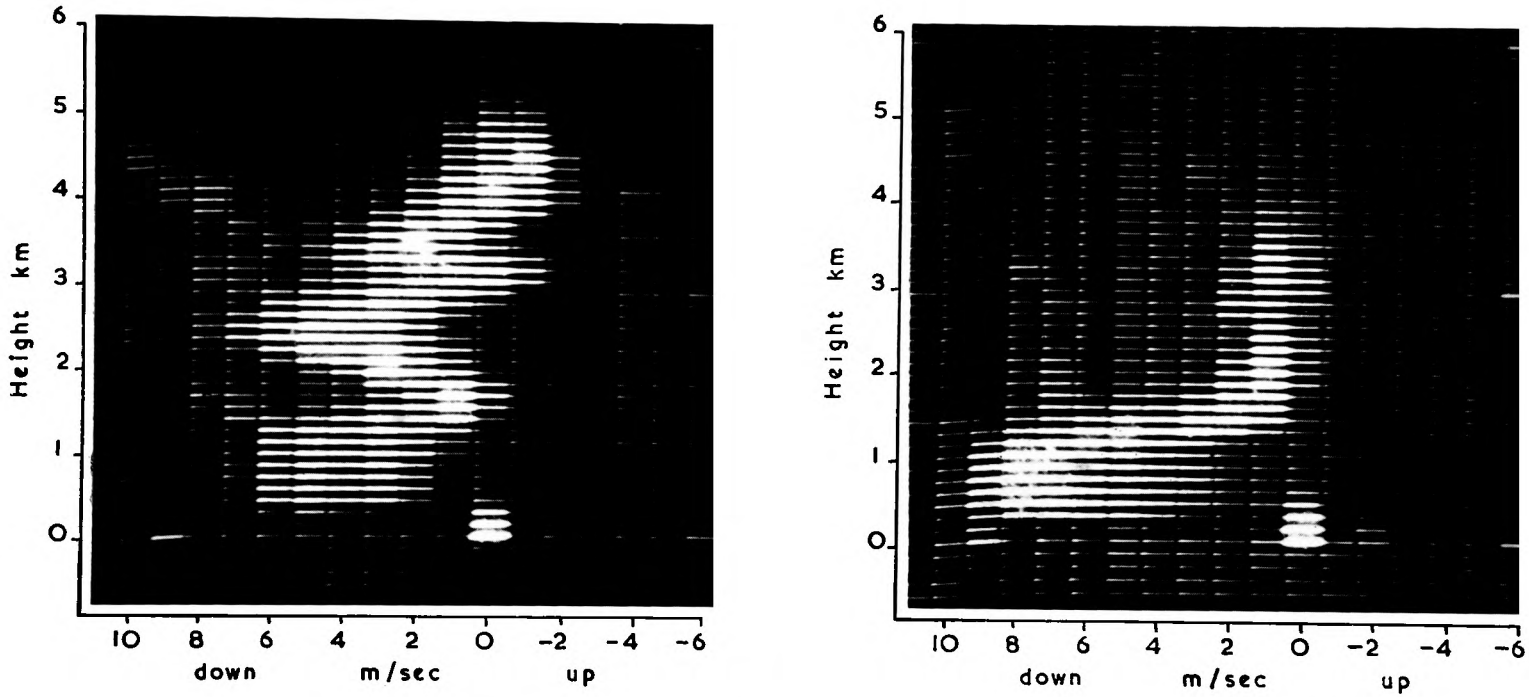
Interpretation of particle terminal velocities 6

Consideration of individual shower analyses 9

Discussion 30

Acknowledgements 32

Bibliography 32



(*a*) Active section at 1235 GMT (*b*) Decaying section at 1250 GMT

PLATE I—Pulsed Doppler radar records from a shower on 8 June 1961 as it moved over the radar.

A Study of Vertical Air Motion and Particle Size in Showers Using a Doppler Radar

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SUMMARY

A 3·2-cm pulsed Doppler radar has been used to record the vertical velocities of precipitation particles within showers. By making assumptions concerning the minimum terminal velocities of the particles, the pattern of the vertical component of air motion may be derived. The validity of the assumptions and the factors which artificially broaden the spectrum of observed velocities are discussed, and an attempt is made to infer particle sizes and densities corresponding to the implied range of terminal velocities. The analyses of seven Doppler sections are described in detail. The major growth of the precipitation particles has been associated with the regions of upward air motion towards the top of echo. An abrupt increase in the width of the velocity spectrum just below the 0°C isotherm is a convincing indication of the presence of the ice phase aloft, but if this increase is not observed there remains uncertainty concerning the nature of the particles aloft. In one instance deductions were made from a systematic change in shape of the power–velocity distribution.

1. INTRODUCTION

Since 1959 the Meteorological Office Research unit at the Royal Radar Establishment, Malvern, has had the opportunity to use a pulsed Doppler radar of 3·2-centimetre (cm) wavelength to study precipitation processes. One of a number of investigations has been of the vertical air motion and particle size in showers. Three analyses of vertical air motion have been presented by Probert-Jones and Harper.[1]* The present paper describes the continuation and extension of their work.

Examples of pulsed Doppler radar records from a shower were published in reference 1. They, and the more recent records, were obtained at Pershore, Worcestershire, 52°09′N 02°03′W, 40 metres (m) above mean sea level, using equipment described by Boyenval,[2] and also by Caton.[3] This equipment measures the radial velocities of the targets from the Doppler frequency shift in the returned signal. The information is produced in discrete form and displayed as a matrix (see Plate I) on a cathode-ray tube, each row corresponding to a range interval of about 150 m (500 feet (ft)) and each column to a velocity band of 1 metre/second (m/s). The zero velocity is indicated by the strong echo (e.g. from stationary ground targets) in the lowest height elements. This zero is set in the middle of a channel which thus covers the range −0·5 to +0·5 m/s; the 1 m/s channel covers the range +0·5 to +1·5 m/s, etc. The echo from scatterers in each range interval and velocity band is summed and presented on the cathode-ray tube as intensity modulation. The display is photographed, each picture having an exposure of about 5 s and during this time about 50 Doppler analyses are superimposed. The velocity channel showing the strongest signal may be assessed from the visual intensity of the display, but precise information regarding signal strength is not available for showers described in this paper.

The aerial is used pointing vertically. The observed velocities towards the radar are thus the sum of the downward velocities (terminal velocities) of the particles through the air and the upward

* The superscript figures refer to the bibliography on page 32.

(−ve) or downward (+ve) component of air motion. The beam is narrow (beamwidth to half-power points is 1·5 degrees, equivalent to 130 m at height 5 kilometres (km)) and at any one height or any one time is unlikely to enclose a region of upward as well as a region of downward air motion. Therefore, following Probert-Jones and Harper,[1] the author attributes the breadth of the velocity spectrum at one level primarily to the range of particle sizes present and assumes that displacements of the spectrum as a whole may yield information on the variability of the vertical component of air motion.

2. METHOD OF ANALYSIS

In order to derive the vertical air motion above the 0°C isotherm, it is assumed that ice crystals or supercooled water droplets with terminal velocity 0·5–1·5 m/s are present in sufficient numbers to give a detectable signal. Below the 0°C isotherm (strictly, below the zone where snowflakes are melting) it is considered that the concentration of small drops is reduced by coalescence (analogy with observations in widespread rain—Caton[4]) and that the minimum terminal velocity detectable is 1·5–2·5 m/s. Thus displacement of the observed minimum velocity from the 1 or 2 m/s channel respectively indicates the presence of vertical air motion. By repeated observations as the shower passes over the radar, a height–time section of vertical air motion is obtained, subject to the validity of the above assumptions.

The assumptions are discussed in Section 3 and it appears that the uncertainty in air motion often approaches 1 m/s, in addition to the uncertainty arising from the discrete form of velocity presentation. A few occasions where the assumptions have introduced greater errors will be mentioned in the description of individual cross-sections. An independent check on the vertical air velocity in the rain region is often possible since, unless hail is also present, the terminal velocity of the largest stable particles does not exceed about 9 m/s near the ground or 10–11 m/s aloft.

The velocity spectrum width, that is the number of channels containing signal, is also recorded as a function of height and time, and cross-sections of this quantity will be discussed for each individual shower. After correction for effects to be discussed in Section 4 and in combination with the minimum-velocity assumptions, the spectrum width indicates the maximum terminal velocity of particles producing echo. Additional cross-sections of the velocity of particles producing the strongest signal (both the velocity relative to the ground and the velocity relative to the air) will be considered for one shower.

The information derived from the Doppler analyses is correlated as far as possible with information obtained from conventional radars observing the shower whilst it approaches, is over, and recedes from the Doppler radar. For this purpose two 3·2-cm range–height radars (AN/TPS-10, vertical beamwidth 0·7°) are operated, one at Pershore and one at Malvern, 20 km distant. A plan-position 10-cm radar (AA Type 4, Mk 7) is also operated at Pershore. Rainfall information is obtained from standard recording rain-gauges (including one open-scale instrument) at the Meteorological Office, Pershore, 0·5 km east of the Doppler radar, and from a special rate-of-rainfall recorder, registering one-minute totals, on the roof of the radar laboratory.

The following three sections discuss the assumptions concerning the minimum detectable particle velocity, the factors affecting spectrum width and the interpretation of particle terminal velocities. The reader who is not concerned with the detail of these topics may proceed direct to Section 6.

3. DISCUSSION OF THE MINIMUM-VELOCITY ASSUMPTIONS

Above the 0°C isotherm

The assumption used in this paper (see Section 2) is the same as that proposed by Probert-Jones and Harper.[1] These authors specifically mentioned the presence of ice crystals and based their assumption on the observation of an acceleration zone at the melting-level in all the Doppler records then examined. The present author agrees that the velocity of the particles towards the ground almost always increases at a level just below the 0°C isotherm in showers at Pershore, but he has noted a tendency for this level to be within a broader zone of increasing downward air motion. Thus an increase of the observed velocity at this level may be due to increasing downward air motion rather than acceleration of particles through the air following melting. However an increase in spectrum width in a narrow layer just below the 0°C isotherm is a convincing indication of melting and, when this occurs, there is clear evidence supporting the basis of Probert-Jones and Harper's assumption. Further the absence of such an increase in spectrum width is not necessarily evidence of the absence of the ice phase above the 0°C isotherm; graupel and large hail may melt gradually over a substantial height interval, perhaps shedding melted water *en route*, and it is probable that high-density ice particles undergo little change in velocity on melting.

If in a particular shower the ice phase is absent above the 0°C isotherm, the assumption that there are particles falling at 0·5–1·5 m/s implies that supercooled water droplets of diameter 130–340 micrometres (μm) are present in sufficient numbers to give a detectable signal (and that such sizes are the minimum detectable). This may be justified by consideration of the radar sensitivity and the droplet size spectra observed in cumulonimbus clouds by Wieckmann and aufm Kampe.[5] Although these measurements were made in 'warm' clouds and at heights 2–6 km above cloud base, there is evidence that drops of these diameters, though initially formed in updraughts, become widely distributed by turbulent mixing in clouds of age exceeding 30 minutes (Browne, Day and Ludlam;[6] Murgatroyd and Garrod[7]). If the assumption should fail, and there is underestimation of upward air motion, the underestimation seems most likely (*a*) in updraughts where the temperature is higher than −10°C or (*b*) in regions of precipitating raindrops (either above or below the 0°C isotherm since this has no special significance) because of sweeping-up of the small drops by the faster-falling large drops. The range of observation obviously affects the radar detection capability, but this is not considered to be the most important factor.

The factors increasing the velocity spectrum width are discussed in the next Section. To the extent that these influence the observed minimum velocity they lead to errors in the deduced air motion, an overestimation of updraughts and an underestimation of downdraughts. Within the more active portions of shower clouds, turbulent air motions on a scale less than the beamwidth will almost certainly cause response of the 0 m/s (−0·5 to +0·5 m/s) velocity channel even in the absence of overall upward air motion. Thus it is considered that a significant updraught should not be inferred unless the minimum velocity moves into the −1 m/s channel; on the other hand significant downdraught is probable when the minimum velocity is displaced to the +2 m/s channel. The cross-sections of vertical air motion show isopleths −1 and +1 m/s corresponding to the boundaries of significant updraught and downdraught as defined above, and leave in between a region of indeterminate small air motion. Provided that a residual uncertainty approaching 1 m/s in vertical air motion is borne in mind, the above procedure seems satisfactory for showers observed at Pershore. However, further consideration is necessary in regions of rapid horizontal or vertical gradient of air motion, on occasions of strong horizontal wind, and generally of recordings in more active thunderstorms where turbulence may be greater and sidelobes of the radar beam may be significant.

Below the zone of melting of snowflakes

Probert-Jones and Harper assumed continuity of vertical air motion at the melting-level and deduced the terminal velocity of the largest drops present immediately below this level. This terminal velocity of the largest drops was then assumed constant during the fall to ground and changes in air motion were inferred from any displacement of the observed maximum velocity. As the authors recognized, the method does not allow for any change in drop-size distribution due to shear across the beam, nor possible growth of the drops due to accretion of water droplets; however, it is reliable should evaporation occur below cloud base because the largest drops are least modified in size and their velocity is least size-dependent.

An alternative assumption, which avoids assuming that there is no change in vertical air motion at the melting-level, is that in the rain region the velocity through the air of the slowest-falling detectable particles is close to 1·5 m/s, after allowing for the effects of turbulence as in the previous sub-section. This assumption is based on analogy with Doppler radar observations in widespread rain and may be criticized on the grounds that the precipitation-forming mechanism and hence the drop-size distribution may differ in the two situations. However it is relevant to record that a spectrum width of 8 m/s is usually observed during moderate or heavy rain when the largest drops would be expected to have a terminal velocity close to 9·0–9·5 m/s, depending on air pressure and temperature ; also that in very many cases the minimum-velocity assumption (here called method II) leads to the same air motion as the Probert-Jones and Harper procedure (here called method I).

The procedure adopted in this study is to examine first the variation of spectrum width below the melting-level. If the spectrum width decreases downwards and the observed maximum velocity is more constant than the minimum velocity, evaporation is the likely cause and method I is adopted; if the observed minimum velocity is the more constant and the strength of the signals in the lower velocity channels appears effectively uniform with height, a change in the concentration of the larger drops is inferred and method II is adopted. (Instances of the spectrum width decreasing downwards in the lowest levels of analysis, below 750 m, are usually due to receiver paralysis following the transmitted pulse and are analysed through interpretation of any displacement with height of the velocity channel containing the strongest signal.) If the width of the spectrum increases downwards either growth of the raindrops by accretion or a change in drop-size distribution through shear may be inferred; in either case method II is adopted. If the spectrum width is constant with height method II is again followed, although usually method I would lead to the same value of air motion.

On a few of the occasions of very heavy rain, usually accompanied by downdraught, the spectrum width is less than 8 m/s. Since it is likely that the largest drops have terminal velocities of 9·0–9·5 m/s the failure of the minimum-velocity assumption is accepted, and the air velocity is determined from the observed maximum velocity towards the ground. Two such cases will be mentioned later. The volume concentration of the 2 and possibly 3 m/s drops is assumed to be below the minimum detectable because of coalescence or size sorting.

4. FACTORS AFFECTING THE VELOCITY SPECTRUM WIDTH

In addition to the range of particle terminal-velocities, several factors may contribute to the velocity spectrum width:

(i) *Variation of the vertical air velocity within the pulse volume.*—The information in an individual height element, involving a range gate of 1·0 microsecond (μs) and a pulse duration of 0·8 μs,

represents a summation over a zone 270 m deep. The horizontal extent of each individual sample is a function of height, being determined by the beamwidth and the horizontal movement of the shower within the photographic exposure time; it is 230 m at 5 km if the shower is moving at 20 m/s. This factor is important only in regions of pronounced horizontal or vertical gradient of air motion but, even in showers at Pershore, it has occasionally contributed at least 2 m/s to the spectrum width. The deduced vertical air motion is the maximum updraught or the minimum downdraught within the pulse volume, subject to the reflectivity and size of the relevant sub-volume being sufficient to give detectable signal.

Photographs at intervals of 5 s are available, but it has not been necessary to analyse all to define the pattern of air motion and spectrum width. Generally, the cross-sections are based on samples at intervals of 10–15 s; thus, except in slow-moving showers, there is little overlap between adjacent samples horizontally, although in an individual sample there is overlap vertically due to the finite pulse duration.

(ii) *Gust velocities superimposed on the vertical air velocity.*—Radar echo fluctuation measurements made with the radar aerial pointing vertically in widespread snow suggest root mean square turbulent velocities of order 0·3 m/s (Rogers[8]). This value is probably appropriate to the decaying portions of showers at Pershore but in the more active parts a somewhat larger value is expected. The spectrum of turbulence within cumulonimbus has been estimated from aircraft responses by Jones[9] and by Steiner and Rhyne.[10] Jones's results suggest that gust velocities $\geqslant$ 1 m/s may be expected once per 200 m of cumulonimbus flying, while the power spectra published by Steiner and Rhyne suggest average velocities of 1–2 m/s for gusts of wavelength $\leqslant$ 150 m in storms of rather greater severity. It is expected that snow or small raindrops will respond readily to turbulent motions, but the same is not necessarily true of the high-velocity particles; for example Stackpole[11] has shown that raindrops of diameter 3 mm may respond to only 70 per cent of the root mean square wind fluctuation. Thus it is thought that in typical showers at Pershore turbulence on a scale less than the beamwidth will not normally cause a variance of the velocity spectrum exceeding 0·6 m/s, except perhaps in regions of strong air velocity or shear. Some support for this claim is given by the consistent nature of the values of air motion and spectrum width obtained from adjacent samples. The spreading of the velocity spectrum due to turbulence has a systematic influence on the deduced vertical air motion which has been considered in the preceding Section.

(iii) *Component of the horizontal wind at the edges of the radar beam.*—As the outer parts of the beam are not exactly vertical, a component of the horizontal wind (U_H) acts towards or away from the radar. This causes a variance of the velocity spectrum of magnitude $0{\cdot}004U_H$ m/s for a 1·5° beam and U_H measured in knots (Hitschfeld and Dennis[12]). Thus even in a 50-knot (kt) wind the variance from this cause is only 0·2 m/s, a lower value than that due to turbulence.

(iv) *Sidelobes of the radar beam.*—The first sidelobe is approximately 3° from the beam axis and the response is lower by a factor exceeding 1000. In a horizontal wind of 50 kt there is a potential variance of the velocity spectrum of 0·8 m/s; however this will be evident only if there are very strong signals near the edges of the Doppler spectrum. At 3° from the vertical the sidelobe is sampling 260 m away from the centre of the main beam at 5 km and horizontal variations of the observed particle velocities (i.e. variations of air motion or particle-size distribution) may be important at times.

The variances due to the separate factors combine in the standard way. Thus if a large variance arises from factor (i) the other factors are unimportant; however if factors (i) and (iv) are not

significant, factor (ii) normally dominates factor (iii). The shape of the spectrum of particle velocities is also important; this may be approximately Gaussian or may be relatively sharp-edged.

The filters which analyse the Doppler frequencies do not have ideally sharp cut-offs. The response of each filter is reduced by a factor of 4 at the cross-over points with adjacent filters and by a factor of about 300 at the centre frequencies of adjacent filters, i.e. 1 m/s off their own centre velocity. If strong signals occur near the edges of the Doppler spectrum some additional broadening may occur from this cause; on the other hand if the Doppler spectrum is approximately Gaussian in shape the reduced response at the cross-over points may diminish the chance of detectable signal appearing in the outer velocity channel.

Because of the discrete form of presentation, a small change of air motion or turbulence may increase the apparent spectrum width by 1 m/s. To reduce the effect of 'chance' changes in spectrum width, adjacent values horizontally and vertically have been summed in fours and isopleths based on the averaged values. To avoid blurring of gradients, vertical air motion values have not been smoothed but isopleths are drawn only if based on at least 3 values.

5. INTERPRETATION OF PARTICLE TERMINAL VELOCITIES

The factors which may contribute to the velocity spectrum width were considered in the last Section. If there is no vertical air motion the lower boundary of the detectable spectrum above the 0°C isotherm probably lies close to 0·5 m/s. If there is a vertical air motion but no variation of mean motion across the pulse volume, the terminal velocity of particles in the mth channel containing signal* is $(m-\frac{1}{2}) \pm \frac{1}{2}$ m/s and the maximum terminal velocity of particles giving signal is probably close to $(n-1)$ m/s, where n is the total number of channels containing signal. If there is variation of the mean vertical air motion across the pulse volume and the spectrum width is broadened 2 m/s from this cause, the mean upward air motion is 1 m/s less than given by the standard procedure, the terminal velocity of the particles in the mth channel containing signal is $(m-1\frac{1}{2}) \pm 1\frac{1}{2}$ m/s and the maximum terminal velocity of particles giving signal is probably close to $(n-3)$ m/s. Terminal velocities below the 0°C isotherm are inferred through similar considerations.

We now consider the relationships between terminal velocity and size for the possible types of echoing particle:

(i) *Terminal velocities of waterdrops.*—Gunn and Kinzer[13] have published the results of a careful series of measurements of the terminal velocity of waterdrops through still air at a pressure of 1013 millibars (mb) and a temperature of +20°C. These may be used to establish a relation between the drag coefficient, C_D, and the Reynolds Number $Re=DV/\nu$, where D and V are the drop diameter and terminal velocity and ν is the kinematic viscosity of the air. For values of $Re<6\times10^2$ ($D=1{\cdot}6$ mm at 1013 mb), C_D is identical with that for a rigid sphere (Goldstein[14]) but, for larger values of Re, the drops are not spherical and C_D is larger than for a sphere. Thus C_D remains between 0·5 and 0·6 when Re is in the range $3{\cdot}8\times10^2$–$2{\cdot}7\times10^3$, corresponding to drop diameters of 1·2–4·5 mm at a pressure of 1013 mb.

* $m=1$ in the lowest velocity channel containing signal ; $m=2$ in the next higher channel, etc.

To estimate the terminal velocity in the free atmosphere, the relation between C_D and Re established by Gunn and Kinzer is assumed to apply aloft. Computations of terminal velocity as a function of the diameter of the equivalent sphere have been made for pressures of 900, 700, 500, 400 and 300 mb and temperatures appropriate to 'cold' and 'intermediate' clouds as defined later in this Section.

(ii) *Terminal velocities of ice crystals and snowflakes.*—The terminal velocities of these particles have been investigated by Nakaya and Terada,[15] Magono[16,17] and Langleben.[18] Cornford[19] has shown that the velocities aloft are given approximately by $V=V_e(\rho_e/\rho)^{\frac{1}{2}}$ where ρ is the air density and subscript e denotes conditions appropriate to the experimental determinations. The terminal velocities vary from 0·3 m/s for plane dendrites to 2·1 m/s for large rimed snowflakes (at 1013 mb); these values are increased by 16 per cent at 700 mb and by larger percentages at lower pressures where, because of the lower temperatures, large rimed snowflakes are less likely. In general, terminal velocities exceeding 3 m/s above the 0°C isotherm must be explained in terms of supercooled water drops or hail.

(iii) *Terminal velocities of hail.*—Nakaya and Terada[15] have measured the terminal velocities of low-density graupel particles. The values of C_D range from 1·35 to 0·96 for Re of $1{\cdot}5\times10^2$ and 5×10^2 respectively, and are 50–75 per cent greater than for spheres of equal Re. List[20] suggests values of C_D between 0·7 and 1·0 for Re from 1×10^3 to 2×10^3, while both List[20] and Macklin and Ludlam[21] find C_D is between 0·53 and 0·75, depending mainly on ellipticity, for large hail stones of $Re>3\times10^4$. There appears to be a dearth of measurements over the range of Re from 2×10^3 to 3×10^4.

Computations of the terminal velocity of spherical ice particles of density 0·1, 0·2, 0·4, 0·6, 0·8 and 0·915 grammes per cubic centimetre (g/cm^3) have been made for pressures of 1013, 900, 700, 500, 400 and 300 mb and temperatures appropriate to 'cold' and 'intermediate' clouds as defined later in this Section. A drag coefficient, C_D, appropriate to spheres has been used for values of $Re<3{\cdot}8\times10^2$, while for larger Re a constant value of $C_D=0{\cdot}6$ has been assumed, permitting substantial simplification of the calculations. The assumptions are similar to those of Browning, Ludlam and Macklin[22] whose analysis of hailstone growth will be referred to in the next two paragraphs. In the description of individual Doppler sections the possible size and density of hail particles will frequently be estimated, based on the above computations. To the extent that the particles are not spherical and have higher values of C_D, the computed velocities are overestimates by up to about 30 per cent and the sizes estimated for a given velocity channel are the minimum appropriate to the velocity.

Macklin[23] has studied in the laboratory the density of rime deposited from a supercooled cloud upon windswept rotating cylinders. The rime density was found to be a function of rU_0/T_s, where r is the droplet mean volume radius, U_0 is the droplet impact speed (somewhat less than the horizontal airspeed U) and T_s is the depression below 0°C of the temperature of the rime surface (raised above the air temperature by the release of latent heat of fusion). Using this result Browning, Ludlam and Macklin[22] have estimated the mean density of ice of diameter 200μm, 1 mm or 2 mm at temperatures of −10, −20 or −30°C in 'cold' and 'warm' clouds, respectively defined as having base temperatures (at 900 mb) of 0 and +20°C (potential wet-bulb temperature θ_w+5 and +23½°C). The authors assumed adiabatic liquid-water concentrations and values for r of 10 and 15 μm in the cold and warm clouds respectively. Values of T_s were estimated from the treatment of the heat economy of spheres outlined by Ludlam.[24]

During spring, showers at Pershore approximate to the 'cold' clouds considered above; however in summer the cloud-base temperatures are intermediate between the cold and warm categories. For this reason estimates similar to the above have been made for 'intermediate' clouds of base temperature +10°C (at 900 mb), θ_w+14°C, and assumed r of 12 μm. Figures 1 and 2 show the calculated mean density of ice particles grown on cores of diameter 200 μm (density of 0·9 g/cm^3) at temperatures of −20°C and −30°C in 'cold' and 'intermediate' clouds respectively. The mean density of particles grown to 4 mm diameter at −30°C and subsequently to larger diameter at −20°C is also shown. The velocity and the melted diameter of the ice particles are indicated. The values of mean density corresponding to $D>3$ mm in the 'cold' cloud are somewhat lower than suggested by Browning, Ludlam and Macklin. This is due to the present assumption of C_D=0·6 in deriving the terminal velocity V (for Re of 5×10^2 to 2×10^3), whereas Browning, Ludlam and Macklin used a lower value appropriate to spheres (C_D of 0·56 to 0·43). Since the true values of C_D possibly exceed 0·6 at these values of Re (List[20]), the Figures may still overestimate the mean density of particles of given D and their velocity (on account of both density and assumed C_D). However, the spread in Macklin's laboratory results and the many assumptions necessary in applying them to conditions in the atmosphere do not justify further refinement of the calculations. The assumption of a core of diameter 200 μm is based on the concept of freezing at temperatures of −30°C to −35°C of cloud droplets which have grown to diameters of 150–200 μm during initial ascent through the cloud, and also that ice splinters produced during the subsequent growth of hail

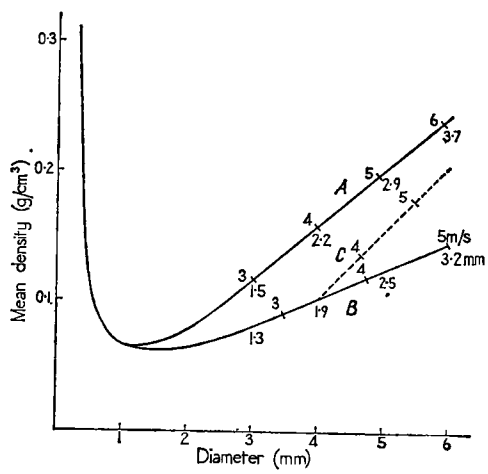

FIGURE 1. Mean density of ice particles grown on the core of a frozen droplet 200 μm in diameter. Temperature 0°C at cloud base at 900 mb and +8·5°C at 1000mb

Curve A — growth at −20°C at 3·75 km

Curve B — growth at −30°C at 4·9 km

Curve C — growth at −30°C to 4 mm diameter, subsequently at −20°C

Single figures to the left of the curves indicate velocities of particles in m/s (assume C_D=0·6 for $Re>400$). Double figures to the right of the curves indicate the melted diameter of particles in mm.

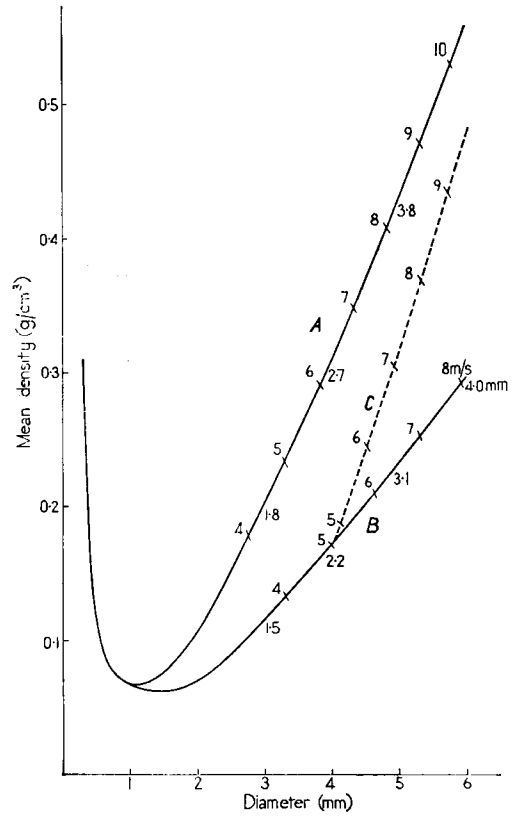

FIGURE 2. Mean density of ice particles grown on the core of a frozen droplet 200 μm in diameter. Temperature +10°C at cloud base at 900 mb and +19°C at 1000 mb

Curve *A* — growth at −20°C at 5·8 km

Curve *B* — growth at −30°C at 7·0 km

Curve *C* — growth at −30°C to 4 mm diameter, subsequently at −20°C.

Single figures to the left of the curves indicate velocities of particles in m/s (assume $C_D=0{\cdot}6$ for $Re>400$). Double figures to the right of the curves indicate the melted diameter of particles in mm.

particles will themselves grow primarily by sublimation (i.e. at high density) until they reach a diameter of approximately 200 μm and acquire significant terminal velocity through the surrounding supercooled droplets.

6. CONSIDERATION OF INDIVIDUAL SHOWER ANALYSES

Between 1959 and 1964 over 20 showers at Pershore have been recorded and analysed. They show great variety and complexity, and little generalization is possible regarding the pattern of air motion. Therefore it is necessary to make a selection and to describe the main features of individual sections, aiming to cover the several stages and degrees of development of showers observed during the programme. Seven shower sections recorded on five days will be described; some of the characteristics are summarized in Table I.

TABLE I. *Characteristics of showers selected for description*

Date	Time GMT	θ_w (cloud base) °C	Height and temperature (section top) *km*	°C	Comments
13.6.60	1116–1143	+9	3·5	−12	Showers of limited vertical extent.
8.4.62	1258–1337	+5	6·1	−40	Typical April showers, much development and decay.
	1411–1424	+5	6·1	−40	
10.5.62	1224–1234	+9	3·7	−16	Single cell, just approaching mature stage.
4.9.62	1312–1348	+13	7·1	−33	Part of decaying shower.
	1441–1505	+13	8·1	−40	Complex shower. Upward motion 8 m/s in new tower at rear.
29.5.64	1517–1545	+15	7·4	−30	Small complex shower—slow movement.

Representation of the Doppler sections in reproducible form is difficult, especially as it is desirable to interrelate the patterns of vertical air motion and spectrum width. In Figures 3, 5, 6, 7, 10, 11 and 12 the outline of detectable signal is shown by a stepped line, the size of the smallest steps revealing the height and time resolution. The left-hand side is the leading edge of the shower and a horizontal distance scale has been added based on the movement deduced from range–height radar observations. The area between the −1 and the +1 m/s isopleths of vertical air motion is one of indeterminate small vertical air motion. The spectrum width is indicated in three broad categories <4 m/s, 4–7 m/s and >7 m/s; thus, above the 0°C isotherm, the unshaded areas probably contain only ice crystals and snowflakes or small supercooled water drops, while the areas of heaviest shading appear to contain (besides slow-falling particles) large particles of graupel or large supercooled raindrops. Additional isopleths of spectrum width are indicated where necessary to clarify points made in the text. The temperature and wind in the undisturbed surroundings are interpolated from radiosonde observations, and the available information on the rate of rainfall is portrayed below the time-scale. The values of vertical air motion and spectrum width in the Figures are those obtained by the standard procedures described in Sections 2 and 3. Modification of the plotted values to take account of special effects will be considered in the text (e.g. substantial overestimation of updraughts due to spectrum broadening other than by normal turbulence, or suspected failure of the minimum-velocity assumptions).

Two points of importance may conveniently be mentioned here. First, the outlines of echo and cloud are not necessarily coincident. There may be substantial areas of cloud in which the particles are too small to give detectable echo; updraughts may predominate in these regions. On the other hand, echo-producing precipitation may fall clear of cloud, e.g. from an anvil, or below cloud base. In these areas evaporation may lead to a failure of the minimum-velocity assumptions. Second, the addition of a horizontal distance scale to the Figures does not imply that a true overall space section has been obtained. The pattern of vertical air motion and spectrum width undoubtedly changes with time, and in a few cases specifically mentioned in the text the observed isopleths could result from development if the space structure was uniform horizontally. Usually however, displacements in 1–5 minutes arising from the observed motions will not cause fundamental changes in the section, and the height–time observations seem to represent fairly closely the spatial structure over the corresponding horizontal distance.

Shower of 13 *June* 1960, 1116–1143 *GMT*

On this date showers were widespread, but mainly light, in a westerly airstream to the south of a depression of 990 mb centred off south-west Norway. During the forenoon a shallow stable layer and dry air above tended to limit convection at about 3·5 km above MSL (−12°C) and it is possible therefore (though by no means certain) that the precipitation was formed without the intervention of the ice phase. The 0°C isotherm was about 1·5 km above MSL. Environmental winds were nearly uniform in direction and speed with height.

Observations over the Doppler radar were made by the Malvern 3·2-cm range–height radar. These suggested that there were three distinct showers, from 1114 to 1121, 1123–1132 and 1134–1142, moving at approximately 32 km/hour (h). It was noted that the major portions of the first two showers (3–4 km in diameter) passed slightly to the north of the Doppler, while the third shower, giving the strongest echo, appeared to pass directly over the Doppler. The Doppler record shows continuous echo from 1116 (the commencement of record) until 1143 but the individual shower characteristic is recognizable in a lowering of the echo top and a general narrowing of the velocity spectrum from 1121 to 1123 and 1132–1134. The open-scale rain recorder at the Meteorological Office, Pershore (0·5 km or 1 minute downwind of the Doppler), confirmed the three-shower structure; maximum rates of 11, 8 and about 7 mm/h were recorded at 1119, 1128 and 1137 respectively and a total of 1·0 mm was measured.

The analysis of vertical air motion depends on the standard assumptions concerning the minimum velocity detectable above and below the 0°C isotherm. If, as is possible, the precipitation in these showers was formed by the coalescence process and the ice phase was virtually absent, the justification for a change in the minimum-velocity assumption at the 0°C isotherm is indeed doubtful. Therefore it may be that some upward air motions above the 0°C isotherm are underestimated by 1 m/s and downward air motions are correspondingly overestimated.

The dominant process in the formation of precipitation cannot always be determined from the existing Doppler radar observations. The observed velocities towards the ground show a pronounced acceleration zone spanning the 0°C level throughout most of the shower; however, this is due to the transition from broadly upward air motion in the top of the cloud to downward air motion in the base. There is no systematic change in spectrum width immediately below the 0°C isotherm, but this is not conclusive since if graupel particles were grown at temperatures about −10°C they would have high density (Browning, Ludlam and Macklin[22]) and their velocity would change little on melting.

The main features of the Doppler record (Figure 3) are:

(i) From 1117 to 1119 at 2½–3 km there is a region of upward air motion of maximum speed exceeding 3 m/s, associated with a maximum of spectrum width of 6 m/s. The high values of spectrum width persist in a column to lower heights where the updraught is weaker. Drops of 1·1 mm diameter have a terminal velocity of 5 m/s at these heights (the balance of 1 m/s spectrum width being associated with factors discussed in Section 4). The largest particles at the top of the echo are falling at 1–2 m/s relative to the ground.

Whilst precipitation particles in an updraught may readily grow until their terminal velocity is equal to the updraught, it is at first sight surprising if those at the extreme top of echo have velocity significantly exceeding the updraught. However, the uppermost height element represents a summation over an interval of 270 m (Section 4), and calculations assuming reasonable water droplet concentrations show that precipitation particles in balance towards the top of the layer may grow by accretion to acquire terminal velocities 1–2 m/s greater than the updraught by the bottom of the layer.

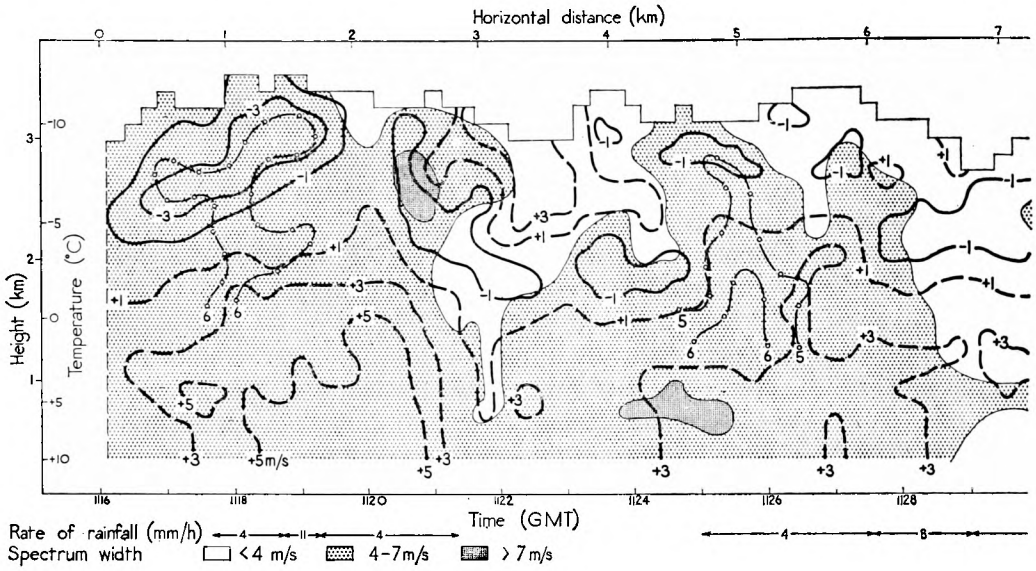

FIGURE 3. Shower of 13 June 1960, 1116–1143 GMT.

——— Isopleths of vertical upward air motion (negative) at intervals of 2 m/s

— — — Isopleths of downward air motion (positive)

o—o—o Additional contours of spectrum width in m/s (see text)

Environmental temperatures and winds are interpolated from radiosonde observations.

(ii) Near 1120 at 2–3 km there is a minimum of upward air motion associated with a minimum of spectrum width of 4 m/s. Only ½ minute later, equivalent to 260 m horizontal distance, there appears a narrow region of upward air motion of 1–2 m/s associated with spectrum widths of 9 m/s or more. Considering the width of the sample at this height (110 m between half-power points) and the strong horizontal gradient of vertical air motion, it appears that the spectrum width may have been exaggerated by 2 m/s even before taking into account the effects of atmospheric turbulence, horizontal wind at the beam edges and frequency filter overlap. Nevertheless it appears that particles of terminal velocity 6 m/s are present and, if these are water drops, they are of 1·5 mm diameter. At the same height from 1122 to 1123 there is a tongue of downward air motion exceeding 3 m/s; in this tongue the spectrum width decreases to 1–2 m/s, characteristic of a subsiding tower. This is one of the regions giving no echo on the Malvern range-height radar and the reflectivity factor is less than 2 mm^6/m^3.

(iii) From 1116½ to 1121½ below 1¾ km (the minimum height of reliable analysis is 0·5 km above MSL) there is a large area of downward air motion, tending to increase towards the ground and reaching 5–6 m/s from 1118½ to 1120½. Reliable values of spectrum width are not available as the maximum velocity coverage of the equipment was exceeded, but estimates range from 4–8 m/s corresponding (after allowance for spectrum broadening) to maximum terminal velocities of the same values. The highest value is certainly not surprising in view of the ground peak rainfall rate of 11 mm/h. Between 1121 and 1123 the downward air motion is generally 1–2 m/s and the spectrum

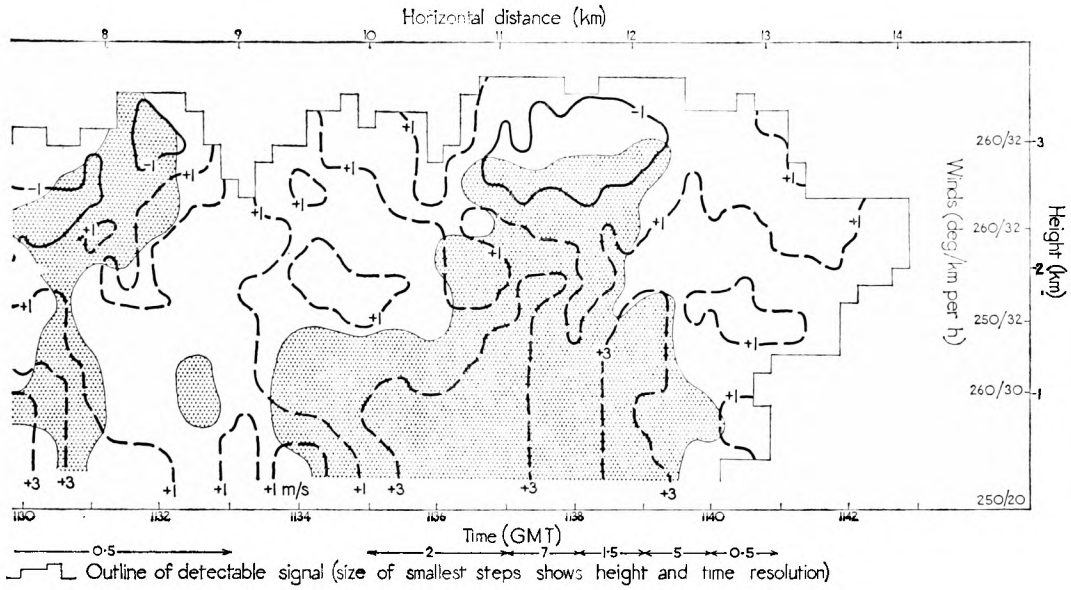

FIGURE 3—*continued*

width 4 m/s, implying a maximum drop diameter of about 1·0 mm. It would be surprising if all these drops evaporated before reaching the ground, but perhaps the rainfall rate was insufficient to record in the gauge.

(iv) Near 1125 and 1127 at 3 km there are peaks of upward air motion exceeding 1 m/s associated with maxima of spectrum width of 5 m/s. High values of spectrum width persist in columns beneath the cells of maximum updraught, implying maximum terminal velocities of 4 m/s at 3 km increasing to 7 m/s at 600 m. These velocities correspond respectively to drop diameters of 0·9 mm and 2·2 mm. A 0·9–mm drop at the top of one of these columns would fall to the base in about 8 minutes and growth to 2·2 mm diameter by accretion of cloud droplets would imply an average liquid water content of about 1·1 g/m^3.

(v) From 1124 to 1131 below about 1½ km there is an area of downward air motion reaching 3 m/s at times. Values of spectrum width near the base of the cloud are 6–7 m/s from 1124 to 1128 decreasing to 3–4 m/s from 1129 to 1131; these correspond to maximum drop diameters of 1·7–2·2 mm and 0·7–1·0 mm respectively.

(vi) About 1132 at 3 km a peak of upward air motion of 2 m/s near the top of the echo is associated with a spectrum width of 5–6 m/s. This corresponds with a tower at appropriate range on a Malvern range–height radar photograph at 1131. A minute or two later the Doppler echo top has dropped appreciably and narrow velocity spectra and general downward air motion are general; this is the region between showers on the Malvern photographs.

(vii) In the third shower from 1134 to 1143 there is relatively little upward air motion, at least in the section examined. Only one substantial cell is found and this is above 2 km from 1137 to 1140 and reaches a peak of 2 m/s. The spectrum width is 4–5 m/s at ½–1 km below the echo top, but at the top the largest detectable particles are stationary relative to the ground. In the base of the shower there is a large area of downward air motion with a peak of 4 m/s at 1¼ km at 1139. The

spectrum width at 600 m is 6 m/s from 1135 to 1138, decreasing towards the end of the shower. This is the shower that was thought to pass centrally over the Doppler and which gave the strongest echo on the Malvern range–height radar. However it is probably significant that the echo strength had diminished since observations four minutes previously. The predominance of downward air motion is characteristic of a shower in the decay stage.

Some further discussion of features of this section, in particular those common to other showers is contained in Section 7 of the paper.

Showers of 8 *April* 1962, 1258–1337 *and* 1411–1424 *GMT*

A west to north-west airstream covered England and Wales, associated with a depression of 990 mb near Denmark. At 1200 the main cold front was well inland over France and the Low Countries and cold polar air extended to tropopause level, 6·9 km, at both Crawley and Aughton. Showers occurred at almost all stations in the United Kingdom, but were mainly slight, up to 5 mm of rain being recorded over a 12-hour period 0900–2100. Winds over Pershore, interpolated from observations at Crawley and Aughton, agree reasonably with the shower movement—from a direction of 270–275°, 66–70 km/h—estimated from radar observations. The 0°C isotherm was at about 800 m above MSL; melting effects were often evident in the lowest level of Doppler analysis.

During approach to and recession from the Doppler radar the showers were studied by the Pershore 3·2-cm range–height radar. A selection of the sections observed with this radar are shown in Figure 4. The range–height patterns are not uniform in horizontal and vertical scale, but are much compressed in range as compared with height. Cores of stronger echo intensity, revealed by gain reduction, are shown shaded in some sections.

The portion of shower which passed over the Doppler radar between 1258 and 1337 must have extended over some 45 km if the estimate of shower movement is correct. The extent of the associated echoes on the range–height sections at various times (as the shower cloud was approaching and receding) is indicated by horizontal lines. These lines fit the echo patterns reasonably well at 1248 and at 1345; however the agreement is less good at 1215, 1228 and 1425 (Figure 4 (*a*)). The effects of increasing range and of attenuation of the radar beam through intervening precipitation contribute to the apparent disagreements, although the major influence is likely to be development and decay of the echo pattern. Thus at 1248 the leading half of the shower is the more active, whereas at 1345 the trailing half of the echo is dominant. The tower at about 28-km range at 1248 would be expected to pass over the Doppler about 1312, but the Doppler record is inactive until after 1320. Thus it appears that the leading portion of the shower is decaying at the time of passing over the Doppler from 1258 to 1320, whereas the trailing portion, which had reached a height exceeding 6 km at 1311, is still active over the Doppler between 1320 and 1337 and later at 1345. It is of interest that the majority of the rain fell before 1320, during the passage of the decaying portion of the echo. The range–height radar sections show a melting band present immediately below the 0°C isotherm throughout this shower and the Doppler radar likewise shows a sharp increase in spectrum width in the lowest level of analysis (Figure 5). Thus it appears that ice crystals and snow are widespread aloft and there seems no cause to doubt the standard assumption concerning the minimum velocity detectable.

The echo associated with the second shower (Doppler section 1411–1424, see Figure 6) is shown in range–height sections at 1335, 1354 and 1425 (Figure 4 (*b*)). In each case the correspondence between estimated and actual range is good. The echo top over the Doppler is 6·1 km at 1415 and this height is exceeded slightly at 11-km range at 1425; thus this shower also is in an active stage. At 1335 the section at azimuth 274° shows clear evidence of a melting band below the

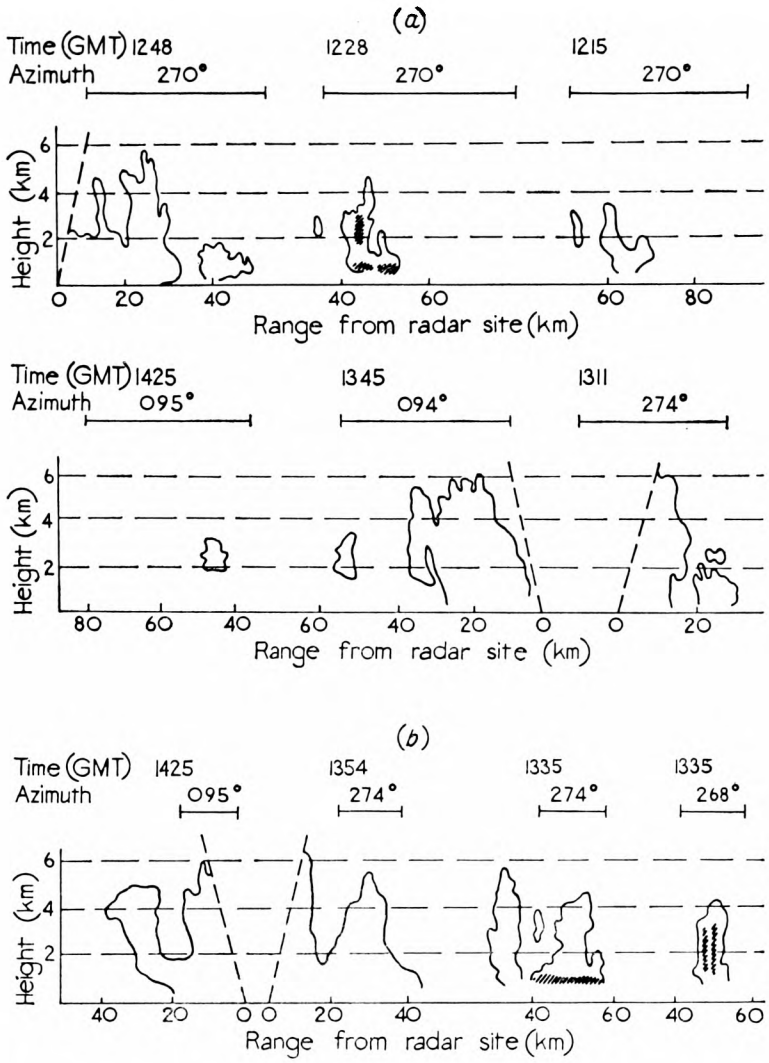

FIGURE 4. Range–height sections of showers of 8 April 1962.

(*a*) Shower over Doppler radar, 1258–1337 GMT

(*b*) Shower over Doppler radar, 1411–1424 GMT

Horizontal lines above the sections show the anticipated extent of echo based on duration over the Doppler and the observed speed of movement. Sloping pecked lines indicate the maximum elevation of the range-height scan. Shaded areas are cores of stronger echo intensity revealed by gain reduction.

0°C isotherm; in contrast the section at 268° shows distinct columns with no trace of a melting band. This suggests that the more active growth is occurring near the southern edge of the shower, which is thought to have passed south of the Doppler.

Thunder was not heard during passage of either of these showers, but was audible twice at about 1400 as a further shower passed just to the south of the Doppler.

The Doppler section for 1258–1337 is shown in Figure 5. From 1320 to 1330 the ratio of the vertical and horizontal distance scales is approximately 4 : 3, but before 1320 and after 1330 the section shows fewer points of interest and the horizontal scale is contracted so that the ratio of vertical and horizontal scales becomes approximately 4 : 1. The main points of interest are:

(i) Between 1258 and 1320 the vertical air motion is small, except for an area of 2 m/s upward motion between 3 and 5 km at 1310. The spectrum width is 1 m/s near the echo top, increasing downwards to 3 m/s at about 1 km; these values are characteristic of ice crystals and snowflakes. However there is a local maximum of spectrum width 3 m/s in association with the updraught maximum at 1310, and a column of the same value extends to 2 km; a similar maximum of spectrum width is associated with an updraught maximum at 5 km at 1317½. It seems that the increased cloud water content accompanying significant upward air motion can readily lead to the production of faster-falling particles, e.g. rimed snowflakes or small graupel. In the lowest level of analysis the spectrum width increases suddenly to 5–6 m/s, indicative of melting to form raindrops of maximum diameter 1·3–1·7 mm.

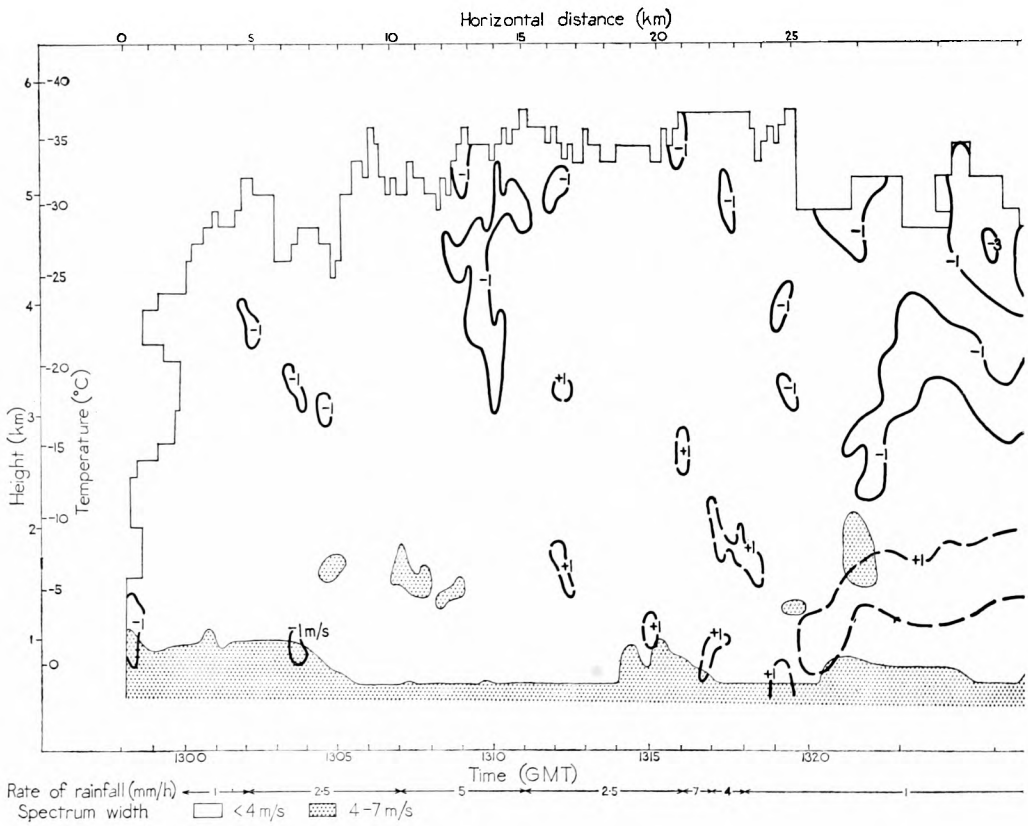

FIGURE 5. Shower of 8 April 1962, 1258–1337 GMT.

——— Isopleths of upward air motion

— — — Isopleths of downward air motion

The horizontal scale is contracted between 1258 and 1320 and between 1330 and 1337. (For other notes see Figure 3.)

(ii) From 1320 to 1330 the vertical air motion is generally upward above 2 km. Maximum speeds of 2–3 m/s occur ½–1 km below the top of the echo at horizontal spacings of 2–3 km. The spectrum width is generally 3–4 m/s. Parts of the echo top are rising at 2 m/s but none of the particles therein is falling relative to the ground. These rising towers are evident at 1322, 1324–1326, 1327 and 1328, whereas at 1323 there is slight downward air motion and low values of spectrum width characteristic of a subsiding tower. Below 2 km the vertical air motion is generally slight. There is one area of downward motion exceeding 1 m/s from 1320 to 1323 and another smaller area about 1329. The spectrum width is 2–3 m/s above 1 km and increases sharply in the lowest level of analysis to 5–6 m/s. This is the equivalent of the melting band seen on the range–height radar.

(iii) After 1330 the vertical extent of echo steadily decreases. Two areas of upward motion occur at 2 km associated with maxima of spectrum width of 4 and 3 m/s. Elsewhere the spectrum width is 1 m/s at the echo top increasing to 3 m/s at 1 km and to 4–6 m/s in rain.

The Doppler section for 1411–1424 is shown in Figure 6. The portions before 1413 and after 1421 are contracted horizontally. The main features are:

(i) Between 1413 and 1419 upward air motion predominates above 2 km. Maximum speeds of 2–3 m/s occur at 4 km at 1413, 1415½ and 1418–1419 corresponding to horizontal spacings of 3–4 km. The spectrum width is 3–4 m/s in and below the regions of strong updraught. At 1414

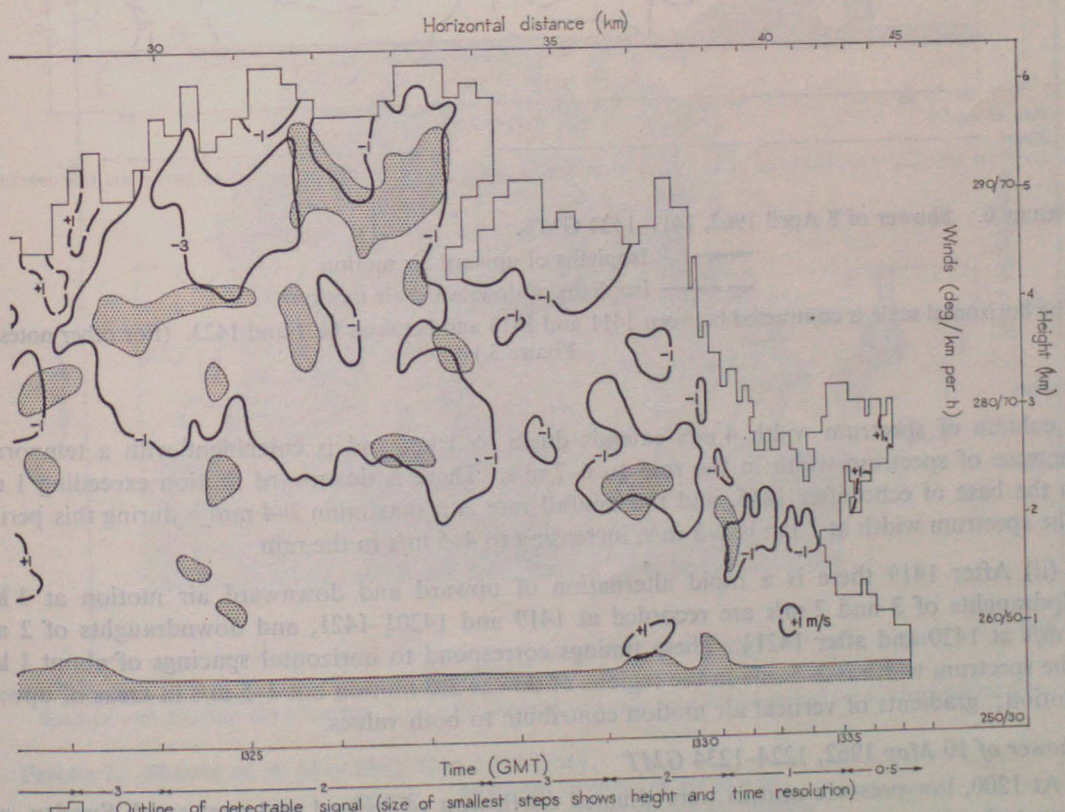

FIGURE 5—*continued*

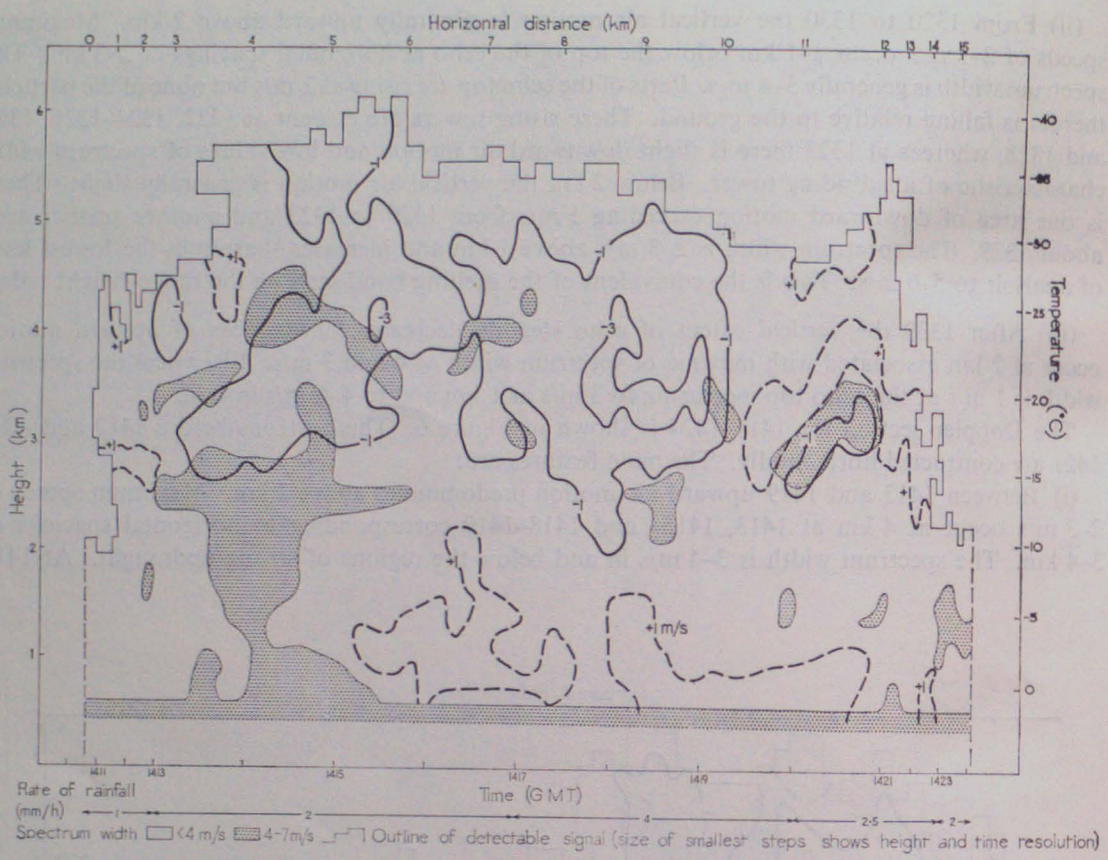

FIGURE 6. Shower of 8 April 1962, 1411–1424 GMT.

——— Isopleths of upward air motion

— — — Isopleths of downward air motion

The horizontal scale is contracted between 1411 and 1413 and between 1421 and 1423. (For other notes see Figure 3.)

a column of spectrum width 4 m/s extends down to 1 km and is coincident with a temporary increase of spectrum width in the rain to 6–7 m/s. There is downward motion exceeding 1 m/s in the base of echo after 1415, and the rainfall rate is a maximum 2–4 mm/h during this period. The spectrum width at 1 km is 2–3 m/s, increasing to 4–5 m/s in the rain.

(ii) After 1419 there is a rapid alternation of upward and downward air motion at 3 km. Updraughts of 3 and 2 m/s are recorded at 1419 and 1420½–1421, and downdraughts of 2 and 1 m/s at 1420 and after 1421½. These timings correspond to horizontal spacings of about 1 km. The spectrum width is 2–3 m/s in the regions of downward motion but 4–5 m/s in areas of upward motion; gradients of vertical air motion contribute to both values.

Shower of 10 *May* 1962, 1224–1234 *GMT*

At 1200, low-pressure centres were situated north-west of Ireland and over south Sweden, and a westerly airstream covered England and Wales. A broad thermal trough over the British Isles

was moving east and showers were reported from most stations in England and Wales. The 0°C isotherm at Pershore was about 1·3 km above MSL, and upper winds were estimated as 270° 26 km/h at 900 mb and 290° 35 km/h at 500 mb. The shower movement derived from radar observations was from about 290° 26 km/h.

The shower was observed by both Malvern and Pershore 3·2-cm range–height radars. Echo was first recorded at 1135 and extended to 4·0 km when 13 km distant from Pershore at 1155. The Malvern radar indicated passage directly over Pershore, the echo then appearing as a single cell about 3 km in diameter, having a top at 3·7 km and a peak reflectivity factor exceeding 10^3 mm^6/m^3; there was no trace of a melting band. At 1320 the Pershore radar observed the shower 26–33 km to the east, with top at 7·5 km. However at 1400 the top was only 6 km and the echo was apparently decaying. At Pershore the rainfall was only 0·1 mm, but it is thought that this may have been exceeded to the east.

The cross-section of vertical air motion and spectrum width is shown in Figure 7, commencement of record being some 15 s after the appearance of echo. Although there is no indication of a melting band on the range–height radar, the derivation of vertical air motion depends on the standard

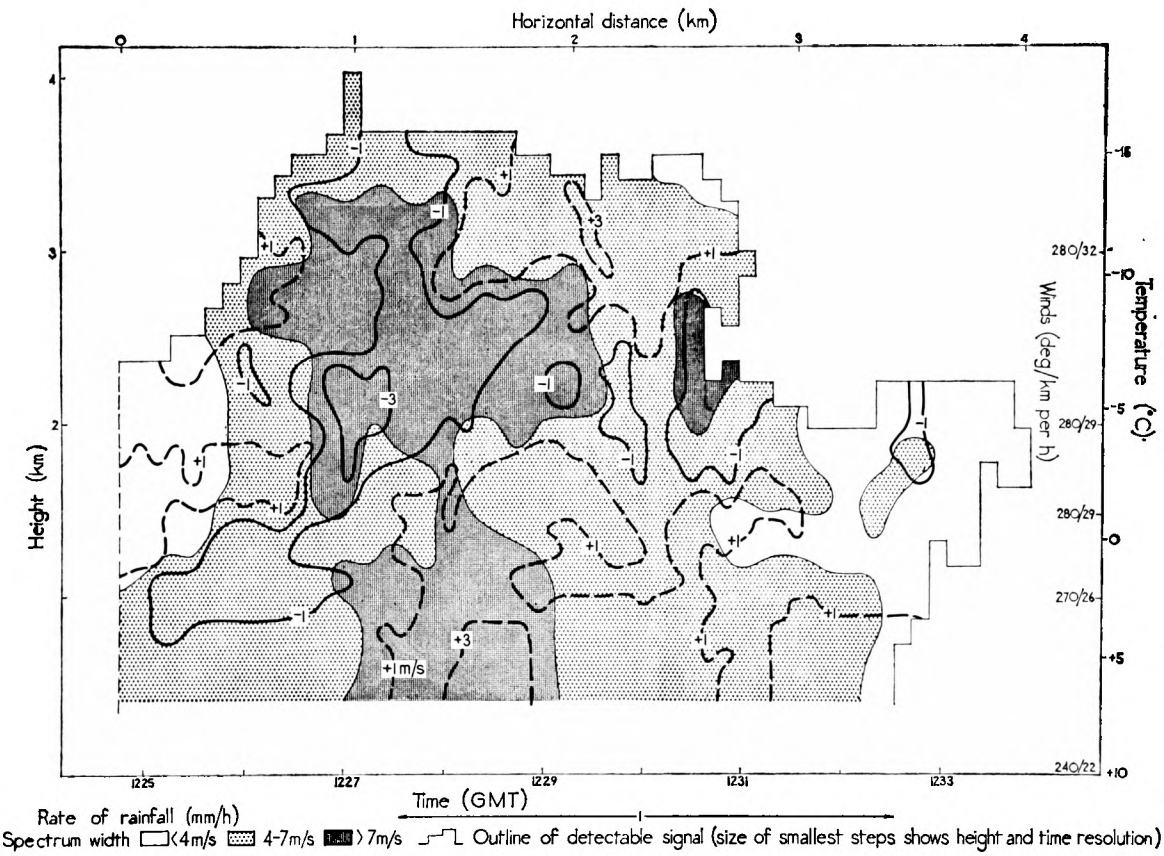

FIGURE 7. Shower of 10 May 1962, 1224–1234 GMT.
——— Isopleths of upward air motion
— — — Isopleths of downward air motion
(For other notes see Figure 3.)

assumptions concerning the minimum detectable terminal velocity. The transition from a minimum terminal velocity of 0·5 m/s to 1·5 m/s is made at 1·1 km and has resulted in some discontinuity in vertical air motion at this level. Despite these uncertainties the overall pattern of vertical air motion is well established.

Figures 8 and 9 show cross-sections of the velocity of particles producing the strongest signal, both velocity relative to the ground (Figure 8) and velocity relative to the air, i.e. the terminal velocity (Figure 9). The channel of strongest signal is usually within 1 m/s of the numerical centre of the velocity spectrum; it thus approximates closely to the mean Doppler velocity (defined as the summation over the channels of the product of echo power and velocity, divided by the similar summation of echo power).

The main features of Figures 7, 8 and 9 are:

(i) Between 1225 and 1229 a column of upward air motion extends from low levels at the front of the shower to the highest echo top at 3·7 km about 1 km behind the leading edge. The slope of this column is approximately 45° at low levels, but becomes nearly vertical aloft. The presence of updraught maxima at 1·0, 2·0 and 3·2 km suggests that the column may represent three rising 'thermals' (between 1226 and 1227 the lowest thermal would rise only about 150 m and thus is distinct from that observed at 2 km).

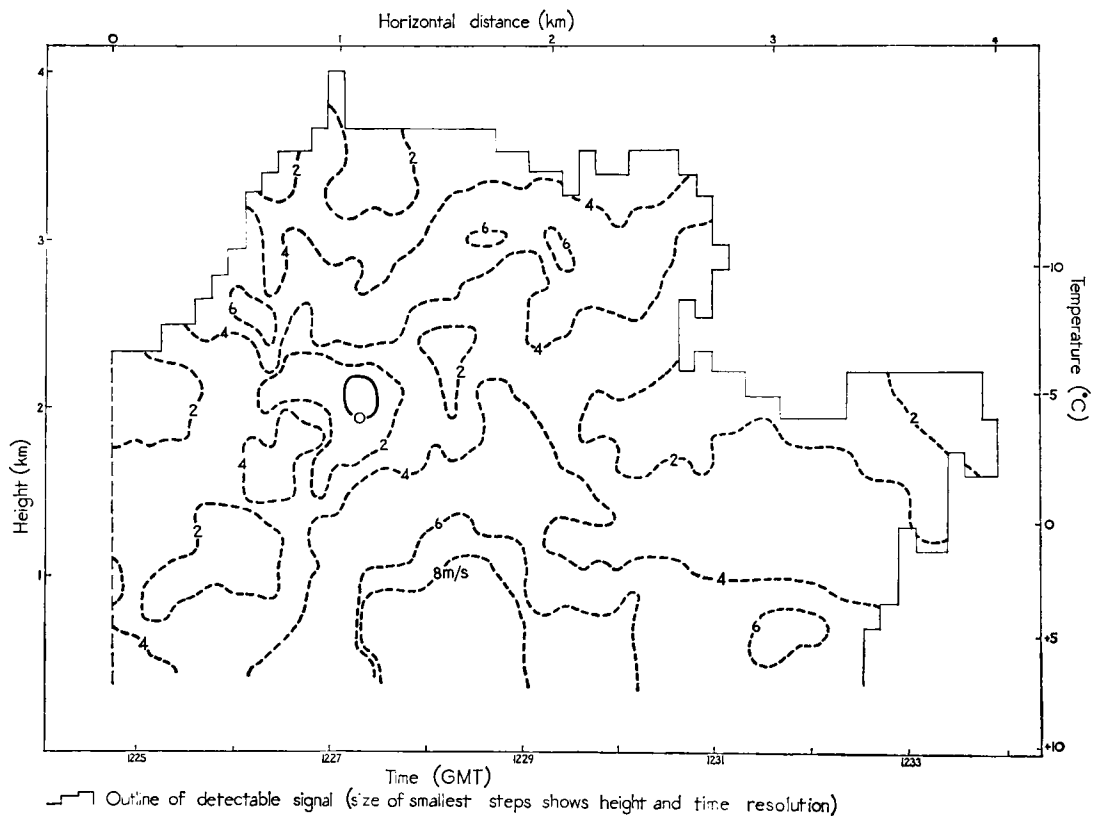

FIGURE 8. Shower of 10 May 1962, 1224–1234 GMT (velocity relative to the ground).
– – – Isopleths of velocity relative to the ground of channel containing strongest signal
Environmental temperatures are interpolated from radiosonde observations.

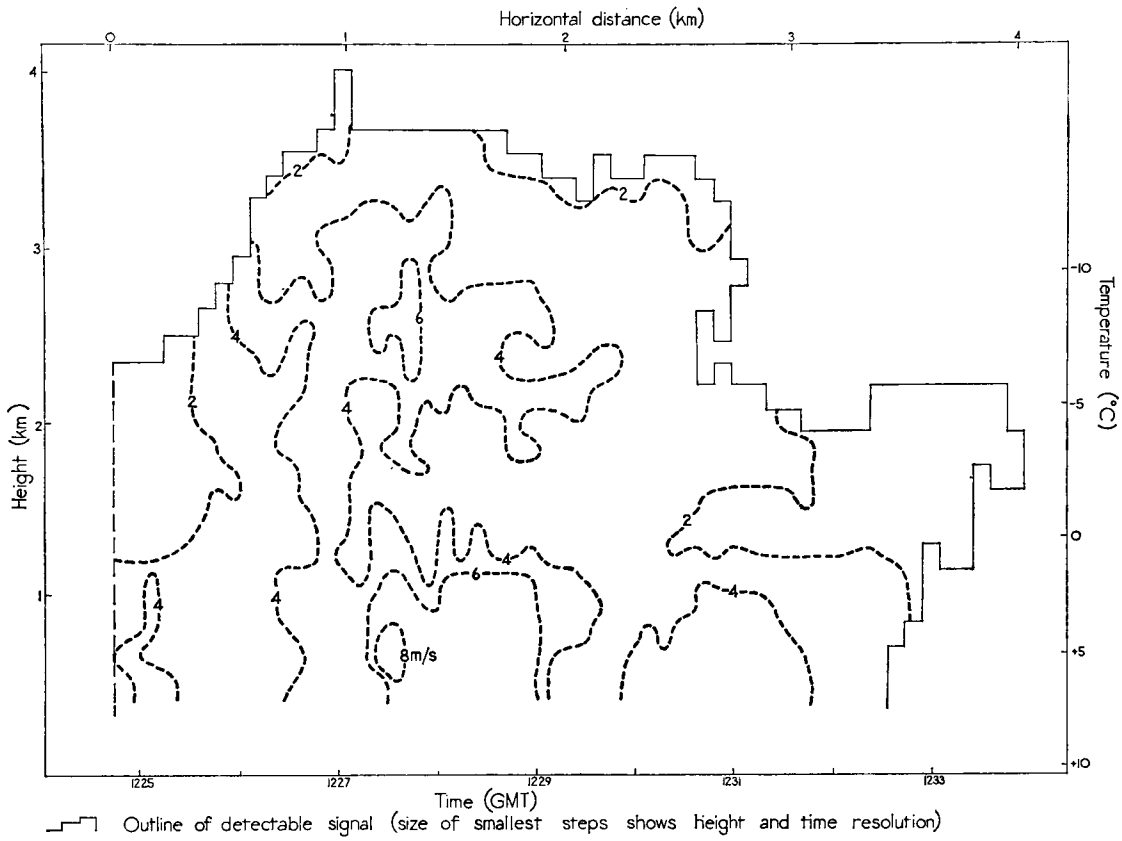

FIGURE 9. Shower of 10 May 1962, 1224–1234 GMT (velocity relative to the air).
– – – Isopleths of velocity relative to the air of channel containing strongest signal
Environmental temperatures are interpolated from radiosonde observations.

At the top of echo the vertical air motion exceeds 1 m/s; however, the spectrum width is 5 m/s and the terminal velocity corresponding to strongest signal is 3 m/s. Thus in the uppermost height element most of the precipitation is falling relative to the ground and the largest particles have speeds which seem unreasonably large assuming growth by accretion within the depth of the element. Explanations in terms of attenuation of the vertically-looking Doppler beam (echo top below cloud top) or of a higher top to one side of the beam are not satisfactory since the observed echo top is equal to that seen obliquely by the Malvern range–height radar. It seems that the precipitation particles must have formed in a previous tower which reached to a somewhat greater height. The high values of spectrum width in the downward air motions in other parts of the echo top support this idea.

The values of spectrum width and of terminal velocity corresponding to strongest signal (Figure 9) increase downwards in the upper part of the updraught column, suggesting growth of the particles by accretion of supercooled droplets. The spectrum width reaches a maximum of 9–10 m/s at $2\frac{1}{2}$ km. Undoubtedly the highest values include an element due to gradients of vertical air motion (the beam is 65 m wide at this height), but it seems that particles of terminal velocity 8 m/s are present. These may be supercooled water drops of diameter 2·0–2·5 mm; however, in view of the temperature of −16°C at the echo top, they are perhaps more likely to be hail. Particles of 3·5 mm diameter and density 0·8 g/cm^3 have the required terminal velocity; the high density is expected since the

core is likely to be a frozen raindrop (rather than a frozen cloud droplet) and the subsequent growth is at temperatures about −10°C. Below 2½ km the spectrum width is generally 6–7 m/s. Evidently the faster-falling particles have not yet penetrated to this region; thus it may be inferred that these particles were formed only some 5–10 minutes previously, probably in the tower which reached above the present echo top.

Figure 8 suggests that, except in one small area, the mean Doppler velocity is downward at all heights. However, just after 1227 at 2·0 km, the strongest signal is from particles either stationary or rising slightly relative to the ground. This region is within that of updraught exceeding 3 m/s. Particles of terminal velocity < 3 m/s are rising, but those near the critical speed will not pass far above 2 km before they grow sufficiently to fall back through the decreasing updraught. On the other hand particles cannot descend through the updraught maximum until they acquire a terminal velocity ⩾ 4 m/s; subsequently they will accelerate downwards through the decreasing updraught. Thus a high concentration of particles of terminal velocity nearly equal to the updraught may develop just above the updraught maximum; this is observed in the present case and may lead eventually to a local maximum of total echo power. (Although the particles continue to grow beneath the updraught maximum, the much reduced concentration due to accelerated downward motion may outweigh the effect on reflectivity of increased size.) Thus the situation of zero mean Doppler velocity, coincident with an updraught maximum and a maximum of total echo power, once established, is likely to be stable. A coincidence of zero mean Doppler velocity and maximum echo power in a convective storm has been directly observed by Atlas, Aoyagi and Donaldson.[25] Of course, not every maximum of echo power nor every updraught maximum is associated with zero mean Doppler velocity.

There is no systematic change in spectrum width near the 0°C isotherm in and below the updraught column. This does not necessarily indicate that the particles above the 0°C isotherm are supercooled water drops. Between 1227½ and 1229 the terminal velocity of the particles giving the strongest signal (Figure 9) increases from 3–4 m/s at 1·2 km to 6½–7½ m/s at 0·9 km and subsequently changes little with decreasing height. The increase is more than can be accounted for by the change at 1·1 km in the assumption concerning minimum detectable velocity. The change in shape of the power–velocity distribution at this particular temperature strongly suggests the melting of ice particles. Whilst hail a few millimetres in diameter and having high density will melt gradually and incur little change in velocity, snowflakes and small hail particles of low or moderate density increase their velocity appreciably on melting. This leads to relative increased signal in the higher velocity channels, even if there is no change in overall spectrum width. Thus it seems that the particles above the 0°C isotherm from 1227½ to 1229 are predominantly of the ice phase. On the other hand, the terminal velocity corresponding to strongest signal shows no pronounced change at the 0°C level from 1226½ to 1227½, and it is suggested that the particles in this region, probably formed in the updraught maximum at height 2 km, are entirely water.

(ii) Regions of downward air motion near the top of echo both before 1227 and after 1228 have already been briefly mentioned. The downward motion exceeds 3 m/s near 3 km at 1229½. The spectrum width is frequently 4–7 m/s, suggesting the presence of particles formed in an earlier updraught. However, in the leading edge of echo, before 1225, the spectrum width is only 2 m/s and increases sharply just below the 0°C isotherm; this suggests the melting of snowflakes and again implies that the ice phase is a significant factor in this shower.

(iii) Between 1229 and 1233 at 2 km there are four areas of upward air motion exceeding 1 m/s. In the first three of these the spectrum width is 6–7 m/s, but it seems clear that the major part of the growth of the larger particles has occurred elsewhere.

(iv) After 1227½ there is significant downdraught in the lower part of the echo, extending above the 0°C isotherm from 1227½ to 1230. The spectrum width is generally 6–7 m/s, but reaches 8–9 m/s below 1 km from 1227½ to 1229. The latter figures indicate the presence of raindrops of diameter exceeding 3·0 mm; such drops should not evaporate substantially in the 600 m above ground and it is surprising that the Pershore gauge recorded only 0·1 mm of rain.

It is thought that this shower is just approaching the mature stage. There is a pronounced updraught and evidence of precipitation particles of substantial size formed in an earlier updraught and continuing their growth in the present column. However, downdraughts form a substantial part of the cross-section and it cannot be long before appreciable precipitation reaches the ground. As already remarked this shower grew to 7·5 km, 30 km east of Pershore. There is convincing evidence on the Doppler record of the melting of ice particles, even though no 'melting band' is seen on the range–height radar even at reduced gain.

Showers of 4 *September* 1962, 1312–1348 *and* 1441–1505 *GMT*

At 1200 a low of 994 mb was centred north-west of Ireland, while a secondary of 996 mb was near south-west Norway. A south-westerly airstream, originally of polar origin, covered England and Wales. A thermal trough near 5°W longitude was moving east and the radiosonde ascent at Camborne at 1130 showed the air to be unstable to a height exceeding 7 km. Light or moderate showers were reported at most stations while thunderstorms occurred at Ross-on-Wye, Shawbury and Elmdon between 0900 and 1500. Hail was observed at Bristol. The 0°C isotherm at Pershore was about 2·1 km above MSL. Upper winds, based on observations at Larkhill at 1130, were 220° 40 km/h at 900 mb, becoming 200° 80 km/h at 500 mb; however by 1730 a veer of wind to 250/240° had extended east to Crawley. The shower movement deduced from radar observations was from 225° 60 km/h for the first shower and 240° 55 km/h for the second.

The first shower was over the Doppler radar at 1312–1348. However, since it then appeared in process of decay, only a part of the section, i.e. 1316–1324, is reproduced (Figure 10). The shower was observed by the Pershore range–height radar at frequent intervals after 1234; even at 1307 the echo top was 7·3 km and there was a prominent echo core (reflectivity factor > 10^4 mm^6/m^3) extending to 4 km at a distance of 11–15 km from Pershore. This might have been expected to pass over the Doppler from 1318 to 1322. However, the Malvern range–height radar confirmed the absence of column structure over Pershore and, after 1318, showed a melting band just below 2 km.

The Doppler cross-section shows that above 3 km there is little vertical air motion. The spectrum width is 1–2 m/s near the top of echo, increasing to 3–4 m/s at 3 km. These values are typical of ice crystals, snowflakes and small graupel particles. Below 3 km, downward air motion of 1 m/s is general. From 1316 to 1319 the spectrum width is 4–6 m/s above the 0°C isotherm, increasing to 7–8 m/s in rain. After 1319 the spectrum width is 3–4 m/s above the 0°C isotherm and increases to 6–7 m/s in rain; however, the transition appears rather sharper than previously and corresponds to the melting band seen on the Malvern range–height radar. The observed peaks of rainfall rate may be identified with downdraughts in the lowest level of analysis exceeding 3 m/s from 1313 to 1315 (not shown) and 2 m/s from 1319 to 1321. The spectrum width of 5–6 m/s above the 0°C isotherm from 1317 to 1318 implies the presence of graupel particles, presumably formed during the earlier more active phase of the shower. In these circumstances the increase in spectrum width with decreasing height may result primarily from terminal velocity sorting of the particles and need not imply substantial growth during descent. Thus ice particles of 4 mm diameter and density 0·3 g/cm^3 have terminal velocities 5·1 m/s at 800 mb and melt to form raindrops of diameter 2·7 mm

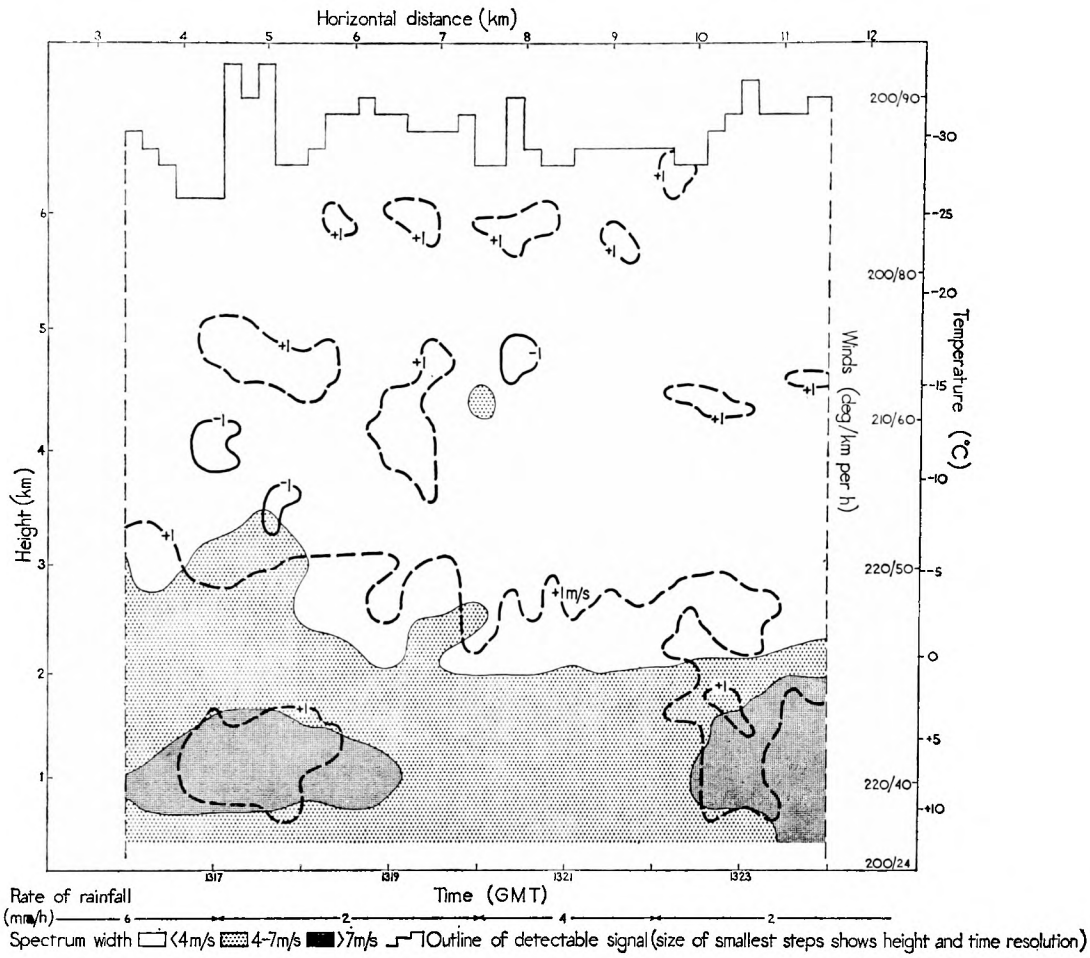

FIGURE 10. Shower of 4 September 1962, 1312–1348 GMT.
——— Isopleths of upward air motion
— — — Isopleths of downward air motion
Only the section from 1316 to 1324 is shown. (For other notes see Figure 3.)

with terminal velocities 8·0 m/s at about 900 mb. The density of the ice particles corresponds to growth at −20°C in a cloud of base temperature +10°C (Figure 2).

The second shower was over the Doppler radar from 1441 to 1505. It was observed by the Pershore range–height radar at 1424 when the highest top, 6·7 km, was at the rear of the shower, corresponding to passage over the Doppler at 1455. The portion of echo over the Doppler radar between 1457 and 1505 appears to be a new development since 1424. The Malvern range–height radar, observing the shower over Pershore, indicated a slight increase in echo intensity just below the 0°C isotherm before 1451, but subsequently there was no trace of a melting band. In fact, columns of strong reflectivity extended to 3 km at 1453 and from 3 to 7 km at 1455½; subsequently peaks of reflectivity occurred at 5 km at 1500 and 6½ km at 1502. These peaks correspond with regions of high spectrum width on the Doppler record.

The cross-section of vertical air motion and spectrum width from 1442 to 1505 is shown in Figure 11. The main features are:

(i) Until about 1446 there is little organization in the pattern of vertical air motion. From 1446 to 1457, upward air motion predominates above 4 km, and a maximum exceeding 5 m/s occurs in a tower from 1455 to 1456. There is a large area of downward air motion below 3–4 km, apparently exceeding 5 m/s near 1 km from 1453 to 1455. However, it may be observed that the spectrum width at this height decreases to 5–6 m/s from 1453 to 1455, which is a surprisingly low value in view of the peak rainfall rate of 10–12 mm/h. It is possible that the minimum-velocity assumption has failed in this region, because of abnormal raindrop coalescence or size sorting of the particles; the largest drops probably have a terminal velocity of 8–9 m/s and the downdraught recalculated on this assumption is 3 m/s. The spectrum width at the top of echo is 1–2 m/s and increases downwards in rather irregular fashion. The value of 6–7 m/s at 4–5 km from 1449 to 1451 indicates that the largest particles there have a diameter of $3\frac{1}{2}$ mm and density 0·25 g/cm^3 (Figure 2); the rapid gradient of spectrum width just above this maximum suggests a concentration of 1·6 g/m^3 of supercooled water droplets. The spectrum width reaches 7 m/s at 7 km at 1456. Although gradients of vertical air motion contribute to this value it seems probable that particles of terminal velocity 5 m/s are present in the tower; in view of the low temperature these are likely to be hail of about 4 mm diameter and density 0·15 g/cm^3. A column of high spectrum width extends downwards to 2 km from 1455 to 1457 and reaches maximum values exceeding 8 m/s at 4 and $2\frac{1}{2}$ km; this would appear to represent particles which commenced their growth at some earlier stage of the tower and have continued growing at progressively higher temperatures during descent. Particles of 5 mm diameter and mean density 0·45 g/cm^3 have terminal velocity about 7·2 m/s at $2\frac{1}{2}$ km. The column corresponds to the core of strong reflectivity seen on the Malvern range–height radar at $1455\frac{1}{2}$.

(ii) Between $1456\frac{1}{2}$ and $1503\frac{1}{2}$ above 5 km there is a large area of exceptionally strong updraught, peak velocities of 6–8 m/s being observed. The top of echo over the Doppler reaches 8·1 km (the environmental temperature is −40°C) at about 1501 and the vertical air motion is 7 m/s. It should be mentioned that the increase in echo top between 1459 and 1501 could represent the change with time in the height of a 'bubble' ascending at 7 m/s, and that the entire record from 1459 to $1503\frac{1}{2}$ may depart significantly from a space section. All of the particles in the extreme top of echo and in fact above 7 km from 1459 to 1502 are rising relative to the ground. The spectrum width increases downwards through the updraught and reaches 8–9 m/s at 4–6 km from 1459 to $1500\frac{1}{2}$ and 11 m/s at $5\frac{1}{2}$–6 km at 1502. The gradient of vertical air motion contributes to the values but it is likely that the largest particles have terminal velocity about $7\frac{1}{2}$ m/s in both centres. These correspond well to the cores of strong reflectivity observed by the Malvern range–height radar. Much of the growth will have occurred at temperatures about −30°C while the particles were suspended in the strong updraught, and thus it is suggested that they have a diameter of $5\frac{1}{2}$–6 mm and density about 0·3 g/cm^3. The high values of spectrum width extend down to about 4 km; at lower heights the spectrum width decreases downwards and below 2 km no echo is detectable. Evidently the large particles formed in the upper portion of echo have not yet penetrated to ground level in this section. The air motion is downward in the lower portion of echo and velocities of 3–5 m/s are suggested below $3\frac{1}{2}$ km from 1500 to 1502. It is possible that this region is cloud-free and that the minimum-velocity assumption has failed because of evaporation of the smaller particles; if so the echoing particles have larger terminal velocity than shown and the downdraught is correspondingly weaker. Finally it may be remarked that the gradient of vertical air motion between 5 and 6 km from 1459 to 1502 implies a horizontal convergence into the layer of 7×10^{-3}/s, an order of magnitude greater than observed on the meso-scale in fronts (Harrold[26]).

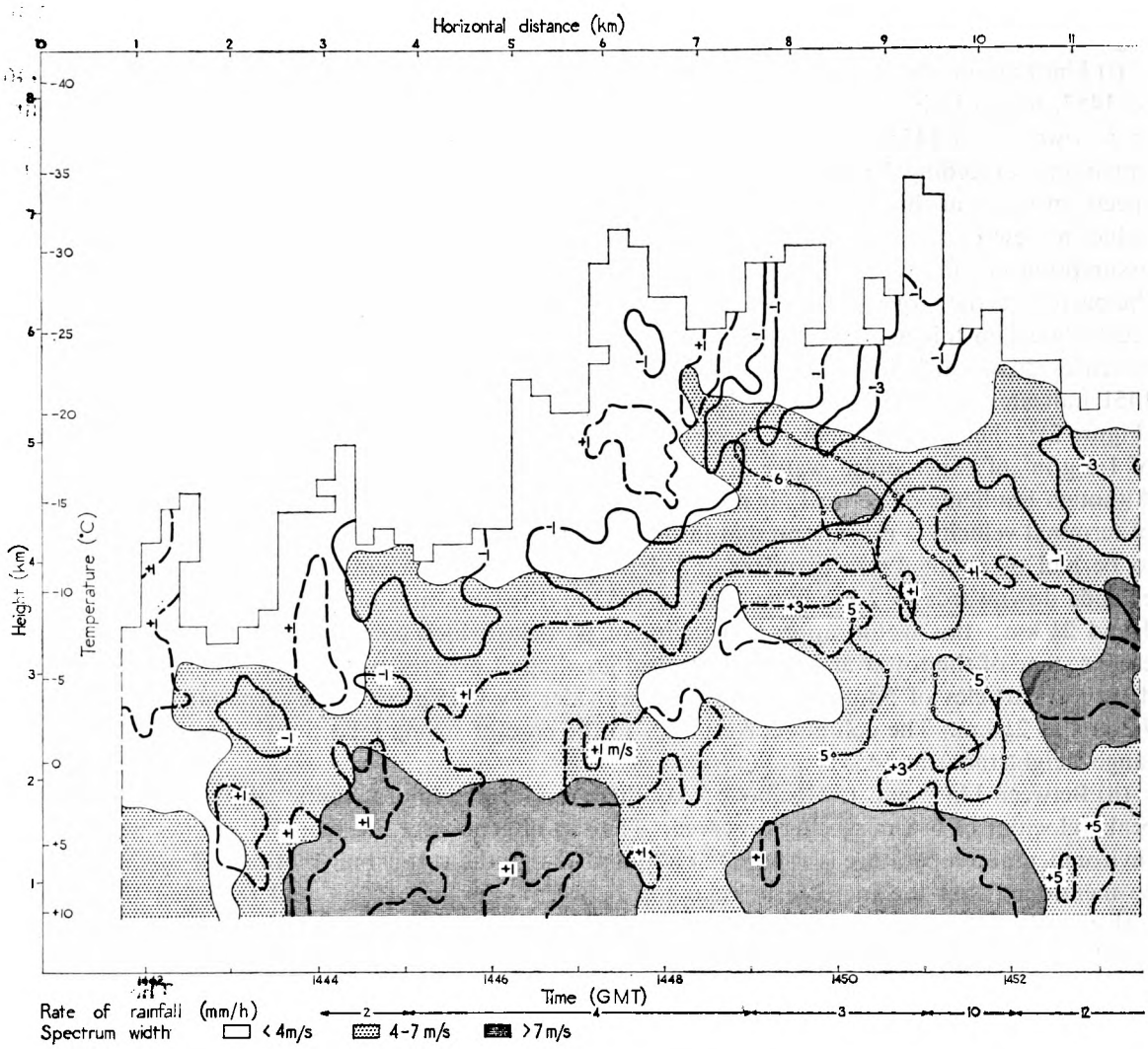

FIGURE 11. Shower of 4 September 1962, 1441–1505 GMT.
——— Isopleths of upward air motion
— — — Isopleths of downward air motion
(For other notes see Figure 3).

Shower of 29 *May* 1964, 1517–1545 *GMT*

The surface weather map at 1200 showed a depression of 984 mb some 500 miles south-west of Ireland, with a ridge of high pressure over the North Sea extending from an anticyclone near Greenland. A cold front from north Ireland to south-west Wales to Dorset was moving very slowly north-east. The radiosonde ascent at Aughton at 1130 showed the air to be unstable for surface temperatures exceeding 21°C. Showers were well scattered, but where they occurred were often associated with thunder. The 0°C isotherm was about 2·6 km above MSL. The upper

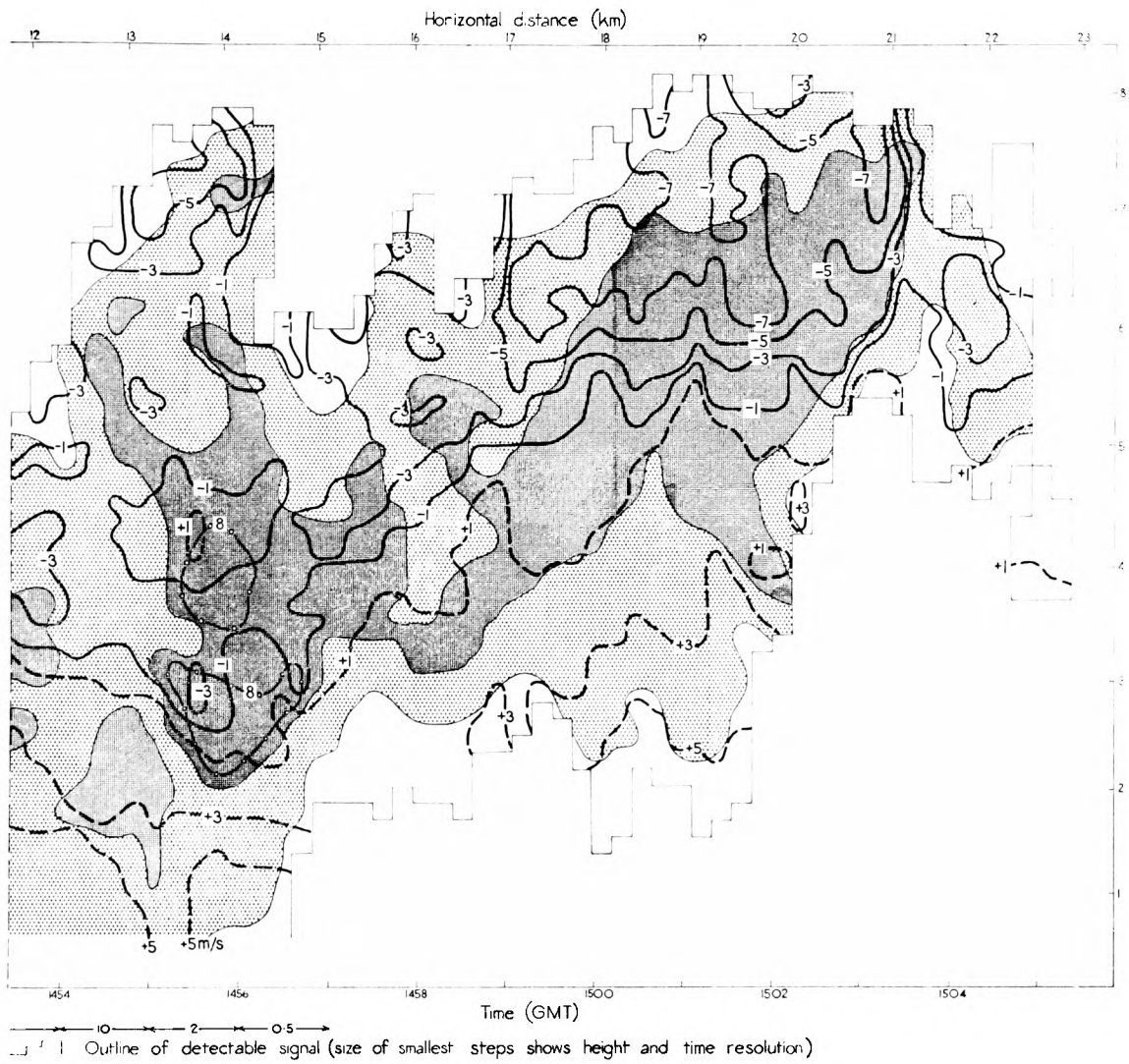

FIGURE 11—*continued*

winds based on observations at Aughton at 1730 were 170° 9 km/h at 900 mb increasing to 170° 26 km/h at 500 mb. The shower movement suggested by radar observations was approximately 11 km/h.

The shower was observed by the Malvern range–height radar between 1500 and 1600. During this period there was little change in form, except for the development between 1517 and 1521 of the tower which passed over the Doppler radar from 1526 to 1528. Otherwise the shower appeared as a single cell, 5–6 km in diameter, having a peak reflectivity exceeding 10^5 mm^6/m^3 at 1531 and 1536. There was no evidence of a melting band even on reduced-gain photographs. The Meteorological Office, Pershore, recorded a rainfall rate of about 60 mm/h from 1530 to 1537 and a total amount of 9·3 mm; the heavy fall is partially associated with the slow speed of movement although the reflectivity in this shower is outstanding amongst those described in this paper.

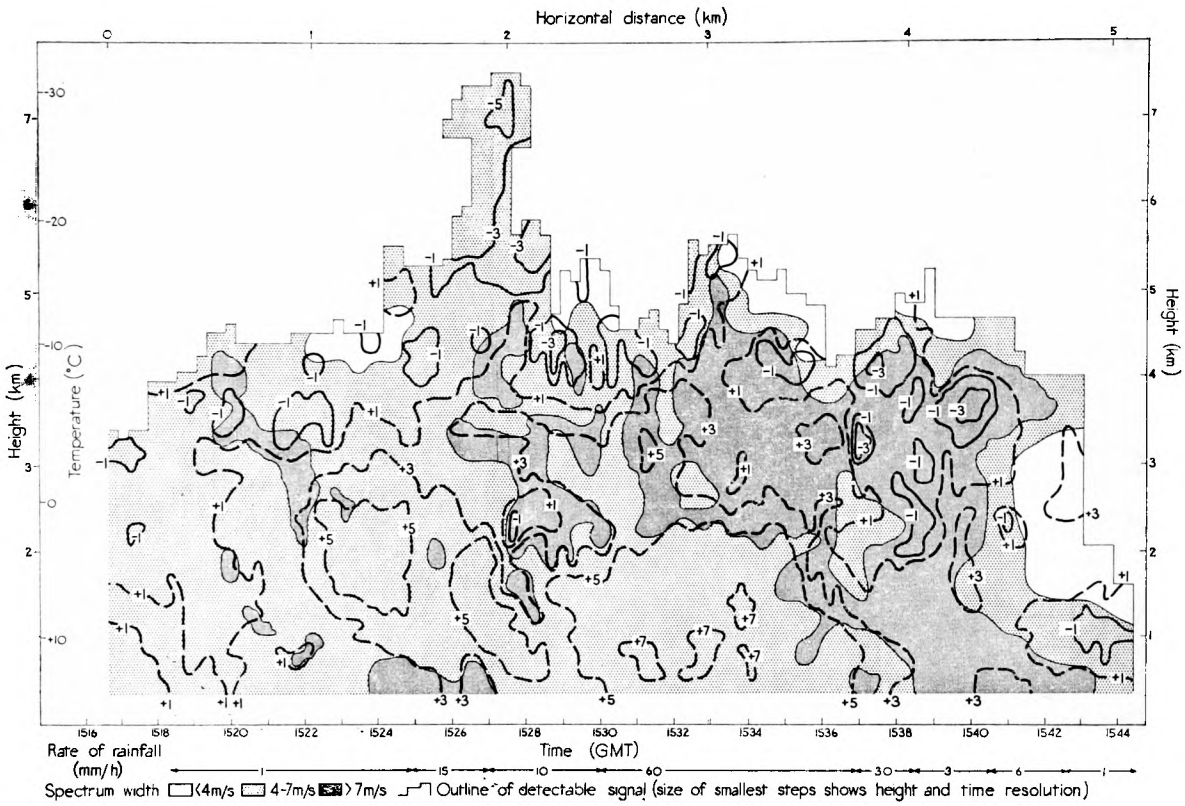

FIGURE 12. Shower of 29 May 1964, 1517–1545 GMT.
——— Isopleths of upward air motion
— — — Isopleths of downward air motion
Winds are light southerly at all levels. (For other notes see Figure 3.)

The cross-section of vertical air motion and spectrum width is shown in Figure 12. Because of the slow speed of movement, the height scale is contracted relative to the horizontal distance scale. Although there is no sign of a melting band on the range–height photographs, nor evidence on the Doppler record of a layer of rapidly increasing spectrum width, it is likely that the ice phase is present at least in the tower over the Doppler radar from 1526 to 1528 (the environmental temperatures were −15°C to −30°C). The analysis of vertical air motion is based on a minimum detectable velocity which changes from 0·5 to 1·5 m/s at 2·3 km, 300 m below the 0°C isotherm. It may be that some upward air motions above 2·3 km are underestimated by 1 m/s and some downward air motions overestimated, but the magnitude and complexity of air motion is such that the uncertainty is of little significance. The main features of the cross-section are:

(i) The Doppler record commences at 1516¾, about one minute after the first appearance of overhead echo. Until 1526 the echo top is 4–5 km and upward air motion predominates above about 3½ km. The spectrum width at the top of echo often substantially exceeds the air velocity and is 5–8 m/s in a region of weak downdraught from 1518 to 1521; thus it appears that the larger particles must have grown in a previous updraught.

The spectrum width increases rapidly in the updraught centre at 3½ km at 1522, indicating substantial growth of the particles in a concentration of supercooled water droplets; a column of high spectrum width extends downwards to 2 km, suggesting that this updraught has been active

for 2–3 minutes at least. After 1520, downward air motion predominates below 3 km. The speed reaches a maximum of 6 m/s near 2 km from 1523 to 1524. The velocity isopleths below 2 km slope towards the rear of the shower, and a similar orientation in spectrum width lines is apparent between 1520 and 1522. Both observations may represent the effect of a time rather than a space variation. The spectrum width in the region of downdraught is generally 5–7 m/s; it shows no systematic change at the 0°C isotherm and only a slight tendency to higher values at low levels. This suggests that there is little growth of the particles in the downdraught, where of course water droplets would be expected to evaporate.

(ii) From 1526 to 1528 there is a tower of ascending air above 5 km. If the speed of movement is reliable the duration over the Doppler corresponds to an apparent width of 200–400 m, of which about 150 m is contributed by the radar beamwidth at 6 km. Upward air motion exceeding 5 m/s is inferred and it is gratifying to record that the Malvern range–height radar observed this echo top to rise 600 m in two minutes. Although some values of spectrum width are influenced by sharp gradients of vertical air motion, it appears that particles of terminal velocity 5–6 m/s are growing in this tower. From Figure 2 (page 9) it is suggested that these are graupel of diameter 4–4½ mm and density about 0·2 g/cm^3. A second tower appears to be forming at 5½ km from 1528 to 1529. Upward air motion exceeding 4 m/s is diagnosed and particles of terminal velocity 5–6 m/s are present some ½ km below the echo top. At the higher temperature, −17°C, the particles may be raindrops about 1·1 mm in diameter or hail particles of high overall density growing upon a frozen raindrop core.

(iii) Between 1526 and 1537 there are several cells of upward air motion above 4 km. A speed exceeding 3 m/s is inferred at 4½ km at 1529. Between the areas of updraught there are regions of downdraught, notably at 1528, 1530 and 1533–1536. The spectrum width increases rapidly in the 1 km below the top of echo suggesting rapid growth of the precipitation particles in a high concentration of supercooled water droplets. Below 4 km there is a large area of downward air motion reaching apparent peaks of 7 m/s at 1 km from 1531 to 1534. However the associated values of spectrum width are low considering the very high rate of rainfall, 60 mm/h from 1530 to 1537. It is probable that the minimum-velocity assumption has failed in this region. If the largest drops have terminal velocity 9 m/s the values of maximum downdraught are reduced to 5 m/s. Very high values of spectrum width, 11–12 m/s, occur between 4 and 3 km at 1533; gradients of vertical air motion contribute to the values, but particle terminal velocities of 10 m/s are indicated at the bottom of the column. Raindrops of 4 mm diameter have velocity 10·2 m/s at 3 km. Alternatively, hail particles of high overall density may be present; for example those of 5 mm diameter and density 0·85 g/cm^3 have the required terminal velocity. The technique of investigating the terminal velocity corresponding to strongest signal has not been pursued in this shower because of the complexity of the Doppler patterns and the uncertainty regarding minimum detectable velocity in parts of the rain region. Therefore it has not been possible to decide whether the particles above the 0°C isotherm are in the water or ice phase.

(iv) After 1537 the complex pattern of vertical air motion is maintained. However the cells of upward air motion are found both near the echo top and at lower levels, while the downward air motion is rather less extensive and weaker. The spectrum width increases rapidly in the updraught centre at 4 km from 1537 to 1538 and high values of spectrum width are general from 4 km to the lowest level of analysis from 1537 to 1540. The values are influenced by the variability of air motion but it is clear that large particles are growing in regions of updraught aloft and that relatively little further growth occurs during descent. At 1½–3 km from 1542 to 1543 the spectrum width is low and substantial downdraught is inferred. It may be that the minimum-velocity assumption

has failed because of evaporation of the smaller low-velocity particles. A rapid increase in spectrum width occurs associated with the area of upward air motion exceeding 1 m/s at 1 km from 1543 to 1544; this is probably associated with replenishment of the smaller particles to concentrations exceeding the threshold for detection.

7. DISCUSSION

It seems convenient to summarize and discuss these results in terms of the three stages of a typical shower cell—the developing, the mature and the dissipating stages—as described by Byers.[27]

It is difficult to observe by radar a cell in the developing stage since for much of the time there is no detectable echo. With a 3·2-cm radar of limited sensitivity the observation of echo implies the presence of precipitation-size particles and the cell may then rapidly transform to the mature stage. The youngest cell amongst those described appears to be that of 10 May 1962 (see p. 18 and Figure 7). The shower was visible on the range–height radar for at least 50 minutes prior to passing over the Doppler radar, but the cross-section that was obtained seems to be that of a relatively new cell from which precipitation was only just reaching the ground. It shows a column of upward air motion comprising three distinct 'thermals' extending from low levels at the front of the shower to the highest echo top, 3·7 km, about 1 km behind the leading edge. The slope of the column is approximately 45° at low levels, but becomes more nearly vertical aloft. Many of the echoing particles at the extreme top of the column are falling relative to the ground and this suggests that they were formed in a previous updraught which reached to a somewhat greater height. There is support for this in the downdraughts at the echo top on either side of the rising column and in the inference that the largest precipitation particles formed in the previous updraught have not yet penetrated below 2½–2 km. The precipitation particles continue to grow whilst falling through the upper part of the present updraught column and it is suggested that the largest particles at 2½ km are supercooled water drops of diameter 2·0–2·5 mm, or more probably graupel particles of diameter 3·5 mm and density 0·8 g/cm^3. At 2 km in the updraught column the strongest signal is from particles stationary or rising slightly relative to the ground. This region is coincident with a maximum of updraught speed and it is suggested that a local maximum of echo power may develop through a 'balance' mechanism. There is no melting band on range–height photographs of this shower, even at reduced gain, and no systematic change in Doppler spectrum width near the 0°C isotherm in and below the updraught column. However, in part of the shower a sharp change in shape of the power-velocity distribution is found immediately below the 0°C isotherm and it is concluded that this is due to melting of ice crystals, snowflakes and small low-density graupel particles. The existence of the ice phase is therefore demonstrated. By contrast it is suggested that the particles falling from the updraught maximum at 2 km (temperature −5°C) are entirely water. In addition to the downdraught at the top of cloud, there is a large area of downward air motion in the base towards the rear and it is from this region that rain has just begun to reach the ground.

The showers of 13 June 1960, 8 April 1962 (the more active portions 1320–1330 and 1411–1424), 4 September 1962 (1441–1505) and 29 May 1964 (Figures 3, 5, 6, 11 and 12) appear, generally speaking, to be in the mature stage. Generalization regarding the pattern of air motion is difficult, but it appears that upward air motion predominates in the upper portion of the echo and downward air motion in the base. The implications of this are not entirely clear, since conditions are probably not steady and a single radar can observe only a two-dimensional section of an essentially three-dimensional structure.

The upward air motion frequently shows maxima ½–1 km below the top of echo at horizontal spacings of 1–3 km. The top of echo frequently appears to be rising and satisfactory agreement is obtained with echo-top developments observed by range–height radars. The largest particles in the ascending echo tops are usually rising or stationary relative to the ground, but where they are falling at 3 m/s or more it seems necessary to infer initial growth elsewhere either in space or time. Sharp gradients of spectrum width occur in many of the updraughts, leading to maximum values in and below the updraught centres. This implies rapid growth of the precipitation particles by accretion of supercooled water droplets. The size and density of the largest precipitation particles may frequently be estimated following the method of Browning, Ludlam and Macklin.[22] The concentration of supercooled water droplets may also be derived in favourable circumstances.

Regions of downward air motion are also found in the upper portion of echoes and the correlation of high spectrum width with updraughts and low spectrum width with downdraughts has been found on many occasions. Downward air motion predominates in the lower portion of echoes. Although this generalization is especially true below the 0°C isotherm, the region of downdraught frequently extends above this isotherm. The downward speed tends to increase towards the ground, at least to the lowest level of reliable analysis, about 600 m above MSL.

Columns of high spectrum width extend down from updraught centres aloft, often implying little change in maximum terminal velocity of the precipitation particles. Some decrease in velocity of a particle of constant size will occur due to the increase in air density. On the other hand, coalescence with smaller precipitation particles and accretion of cloud droplets will tend to increase the size and hence the velocity of the largest particles. However, the concentration of water droplets in the region of downdraught will generally be small. Such accretion as occurs will increase the overall density of any graupel particles present and will tend to reduce and prolong the increase in velocity associated with melting. Thus, while the supercooled water remains, a systematic change in spectrum width associated with the 0°C isotherm may not be obvious. The maximum surface rainfall rates are associated with the strongest downdraughts in the base of echo.

The shower of 4 September 1962 between 1441 and 1505 is noteworthy for the strong upward velocities observed in the recent development at the rear. Speeds of 6–8 m/s are diagnosed above 6 km. High values of spectrum width occur and particle terminal velocities up to 7½ m/s are inferred in locations coincident with cores of strong reflectivity observed by the range–height radar. Since much of the particle growth will have occurred at temperatures about −30°C, a maximum diameter of 5½–6 mm and a density of 0·3 g/cm^3 are suggested. These large particles have not yet penetrated below 2 km in this Doppler section, even allowing for failure of the minimum-velocity assumption due to evaporation of the lower-velocity particles.

The shower of 29 May 1964 is remarkable for the complexity of air motion within what appeared to the range–height radar as a single cell 5–6 km in diameter. A narrow tower of apparent width 200–400 m passed directly over the Doppler radar and upward air motion exceeding 5 m/s was present; the range–height radar observed the echo top to rise 600 m in two minutes. Graupel particles up to 4–4½ mm diameter and density 0·2 g/cm^3 appear to be growing in the tower. Particles of terminal velocity 10 m/s are inferred between 4 and 3 km at 1533; these may be raindrops of 4 mm diameter or hail particles of 5 mm diameter and density 0·85 g/cm^3. There was no systematic change in spectrum width at the 0°C isotherm nor any trace of a melting band on the range–height radar. However, this is not conclusive evidence against hail since particles of high density would melt gradually and incur little change in velocity. On the other hand, apart from the recently developed tower, there is no firm evidence in favour of the ice phase since the observed particle velocities can all be explained in terms of water drops. It was impracticable to draw conclusions from the shape of the power–velocity distribution (as for the shower of 10 May

1962) because of the complexity of the air motion. There is a large area of downward air motion in the base of the shower. It seems probable that the minimum-velocity assumption has failed below 2 km from 1530 to 1537, possibly because of velocity sorting of the drops or abnormal coalescence; nevertheless the maximum downdraught is 5 m/s and is associated with the peak surface rainfall rate of 60 mm/h. The minimum-velocity assumption may also have failed, but because of evaporation, in the trailing edge of the shower at about 3 km.

The leading portion from 1258 to 1320 of the first shower on 8 April 1962 and the section from 1316 to 1324 of the earlier shower on 4 September 1962 (Figures 5 and 10 respectively) are representative of the decay stage. In both cases the showers showed active towers on the range–height radar when approaching Pershore; on 4 September a column of reflectivity factor exceeding 10^4 mm^6/m^3 was observed only 11–15 minutes prior to passage over the Doppler radar. Both sections show that the vertical air motion is slight, exceeding 1 m/s upward or downward in small pockets only; downward motion predominates towards the base of the cloud. Above the 0°C isotherm the spectrum width is low, generally 1–3 m/s, characteristic of ice crystals and snowflakes. However, in the April shower there is evidence that the increased concentration of supercooled water associated with the pockets of significant upward air motion can readily lead to the formation of faster-falling particles. In the September shower, graupel of terminal velocity 5 m/s are inferred just above the 0°C isotherm, the remnant of the earlier more active phase of the shower. The spectrum width increases abruptly just below the 0°C isotherm, associated with the melting band which was visible on the range–height radar in both showers.

This study has revealed the pattern of vertical air motion in a variety of showers at Pershore. The major growth of the precipitation particles has been associated with the regions of upward air motion towards the top of echo and in several cases the size and density of the largest particles can be inferred. An abrupt increase in Doppler spectrum width just below the 0°C isotherm is a convincing indication of the presence of the ice phase aloft, but if this increase is not observed there remains uncertainty concerning the nature of the precipitation particles aloft. In one instance deductions were made from a systematic change in shape of the power–velocity distribution. This technique may be more precise when quantitative measurements of power in individual velocity channels are available from a more advanced Doppler radar which has been developed by the Royal Radar Establishment at Malvern.

ACKNOWLEDGEMENTS

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